Quantum Noise and Low-Temperature Decoherence, Les Houches 2006.

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Thanks: E. Conforti, C. Glattli, M. Heiblum, R. de Picciotto, M. Reznikov, U. Sivan

Noise Outline:

- Quantum noise, Physics of Power Spectrum
- Fluctuation-Dissipation Theorem, in steady state
- Shot-Noise, Excess noise, dependence on full state of system
- Detection: Heisenberg Constraints on Quantum Amps'

Direct observation of a fractional charge

R. de-Picciotto, M. Reznikov, M. Heiblum, V. Umansky, G. Bunin & D. Mahalu

Nature 1997 (and 1999 for 1/5)

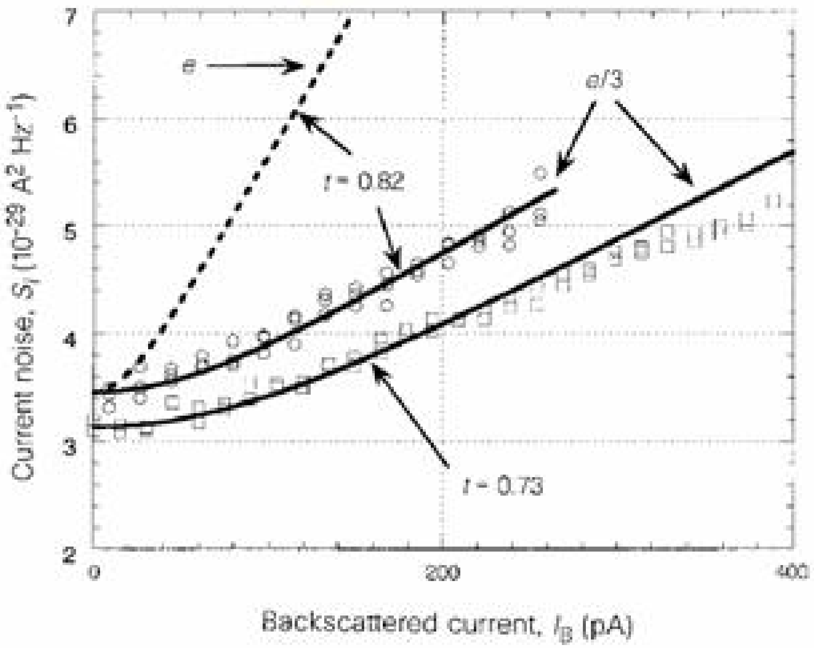


Figure 3 Quantum shot noise as a function of the backscattered current, I_B, in the FQH regime at $\nu = \frac{1}{3}$ for two different transmission coefficients through the QPC (circles and squares). The solid lines correspond to equation (2) with a charge $Q = e/3$ and the appropriate t. For comparison the expected behaviour of the noise for $Q = e$ and $t = 0.82$ is shown by the broken line.

A recent motivation

How can we observe fractional charge (FQHE, superconductors) if current is collected in normal leads?

- Do we really measure current fluctuations in normal leads?

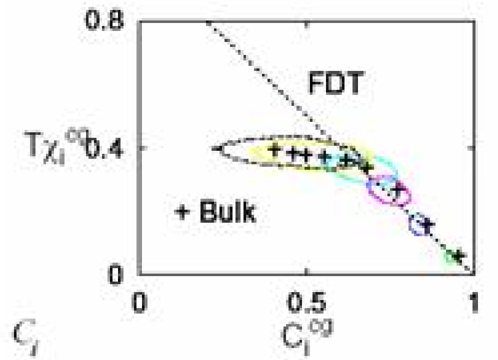
ANSWER: NO!!!

SOMETHING ELSE IS MEASURED.

Second Motivation

Breakdown of FLT in glassy,

"aging", systems:



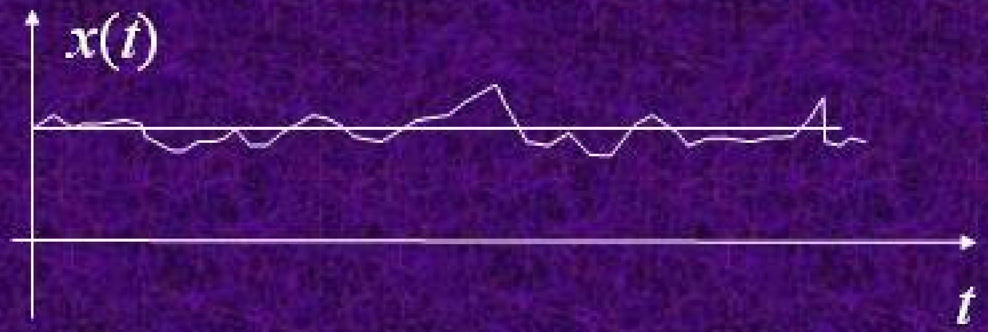
Can we salvage the <u>proper</u> FLT?

(not a stationary system)

Needs Work, but…

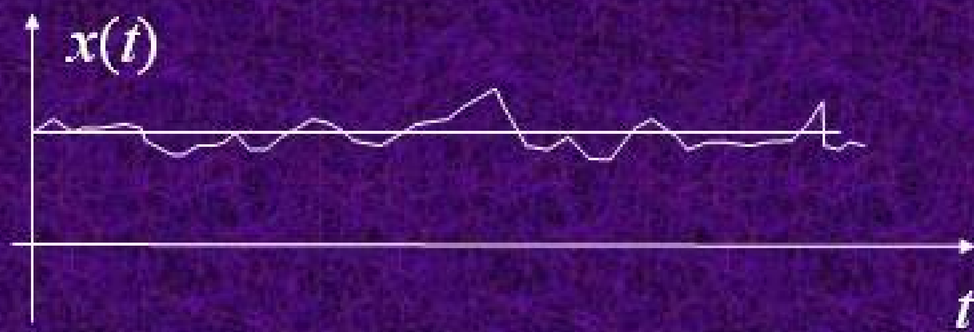
Understanding The Physics of Noise-Correlators, and relationship to DISSIPATION:

Classical measurement of time-dependent quantity, $x(t)$, in a stationary state.



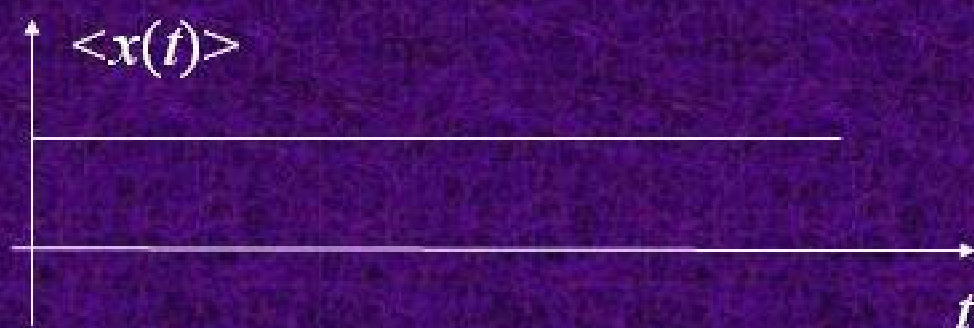
$C(t) = \langle x(t)\, x(t')\rangle$

Classical measurement of a time-dependent quantity, $x(t)$, in a stationary state.



➡ $C(t) = \langle x(t)\, x(t') \rangle$

Quantum measurement of the expectation value, $\langle x_{op}(t) \rangle$, in a stationary state.



➡ $C(t) = ?$

STATISTICAL PHYSICS

by

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Volume 5 of *Course of Theoretical Physics*

Translated from the Russian by Peierls ?

This relation has to be regarded as a definition of the quantity which has been denoted here symbolically by $(x^2)_\omega$. Although the x_ω are complex, the quantity $(x^2)_\omega$ is evidently real. (It is sufficient to remark that the left-hand side of (118.4) differs from zero only when $\omega' = -\omega$, and the change to complex conjugate quantities means changing the sign of ω, i.e. the interchange of ω and ω').

Inserting (118.4) in $\phi(\tau)$ and carrying out the integration over $d\omega'$, we find

$$(x^2)_\omega = \frac{1}{2\pi}\int_{-\infty}^{\infty} \phi(\tau)e^{i\omega\tau}\, d\tau. \qquad (118.7)$$

By treating the quantity x as a function of time, we have implicitly assumed it to behave classically. All the above formulae can, however, easily be re-written so as to apply to quantum-mechanical quantities. For this purpose one has to consider, instead of the quantity x, its quantum-mechanical operator $\hat{x}(t)$, and its Fourier transform

$$\hat{x}_\omega = \frac{1}{2\pi}\int_{-\infty}^{\infty} \hat{x}(t)e^{i\omega t}\, dt. \qquad (118.8)$$

The operators $\hat{x}(t)$ and $\hat{x}(t')$ for different instants of time do not, in general, commute, and the correlation function must now be defined as

$$\phi(t'-t) = \tfrac{1}{2}\overline{[\hat{x}(t)\hat{x}(t')+\hat{x}(t')\hat{x}(t)]}, \qquad (118.9)$$

where the bar denotes averaging by means of the exact quantum-mechanical

The crux of the matter:

The operators $\hat{x}(t)$ and $\hat{x}(t')$ for different instants of time do not, in general, commute, and the correlation function must now be defined as

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where the bar denotes averaging by means of the exact quantum-mechanical

From Landau and Lifshitz, Statistical Physics, '59

From Analysis of correlators:

- **NO PASSIVE ZPF DETECTION,**
- **NEED ENERGY: AMP/"DRIVER"...**
- **ZPF CORRELATOR FROM F.T. of**

  ABSORPTION SPECTRUM.

- **NO DEPHASING as $T \to 0$!**

(BUT: Nearly degenerate ground-state???)

Usual symmetrized correlator/power specrum –

NO GOOD, GIVES MISLEADING RESULTS!

What is the Physical Noise Correlator?

$C(t'-t) \equiv \langle j(t)j(t')\rangle = Fourier\ Transf\ \ of\ \ S(\omega)$

$S(\omega) \propto$ power exchanged with EM field.

Classically, both C and S real and symmetric.

Q. M.: $\hat{j}(t)$ operator, $[\hat{j}(t), \hat{j}(t')] \neq 0$, $[t \neq t']$.

$$C(t) = C(-t)^* \neq C(-t), \qquad S(\omega) \neq S(-\omega).$$

Van Hove (1954), EXACT:

$$S(\omega) = \hbar \sum_{if} P_i |\langle f|\hat{j}|i\rangle|^2 \delta(E_i - E_f - \hbar\omega),$$

$|i\rangle$ – eigenstates, energies E_i, populations P_i.

At equilibrium, temp $T, \Rightarrow$ **Detailed Balance**:

$$S(\omega) = S(-\omega)e^{-\hbar\omega/k_B T}.$$

$S(\omega) = S(-\omega)$ holds only for $\hbar|\omega| \ll T$, $|t| \gg \hbar/T$.

$C(t)$ is not real and not symmetric,

$C(t)$ is not directly measurable,
except via $S(\omega)$, AT BOTH $\omega > 0, \omega < 0$.

Antenna coupled to EM field with N_ω photons.

$$Coupling \cong \frac{\vec{A}}{c} \bullet \int \vec{j}\, d^3r$$

$S(\omega)$ gives:

Emission x'section for $N_\omega = 0$, for $\omega > 0$.

Absorption x'section for $\omega < 0$, for $N_{|\omega|} = 1$.

Easily generalizable to finite $N_{|\omega|}$

$\Rightarrow$ The sign OF ω is RELEVANT

$\Rightarrow$ Symmetrized: $C_s(t' - t) = (1/2)\langle \hat{j}(t)\hat{j}(t') + \hat{j}(t')\hat{j}(t)\rangle$,

is customary, but **BAD**, cf. Lesovik-Loosen.

NO NOISE DETECTED PASSIVELY at $T = ($

NEED: Active Detector, Amplification, etc

Emission = $S(\omega) \neq S(-\omega)$ = Absorption,
(in general)

From field with N_ω **photons**, net absorption

(Lesovik-Loosen, Gavish et al):

$$N_\omega S(-\omega) - (N_\omega + 1) S(\omega)$$

For classical field ($N_\omega >>> 1$):

CONDUCTANCE $\propto [S(-\omega) - S(\omega)] / \omega$

This is the Kubo formula (cf AA '82)!

Fluctuation-Dissipation Theorem (FDT)

Valid in a nonequilibrium steady state!!

Dynamical conductance - response to "tickling"ac field, (on top of whatever nonequilibrium state).

Given by S(-ω) - S(ω) = F.T. of the commutator of the temporal current correlator

Nonequilibrium FDT

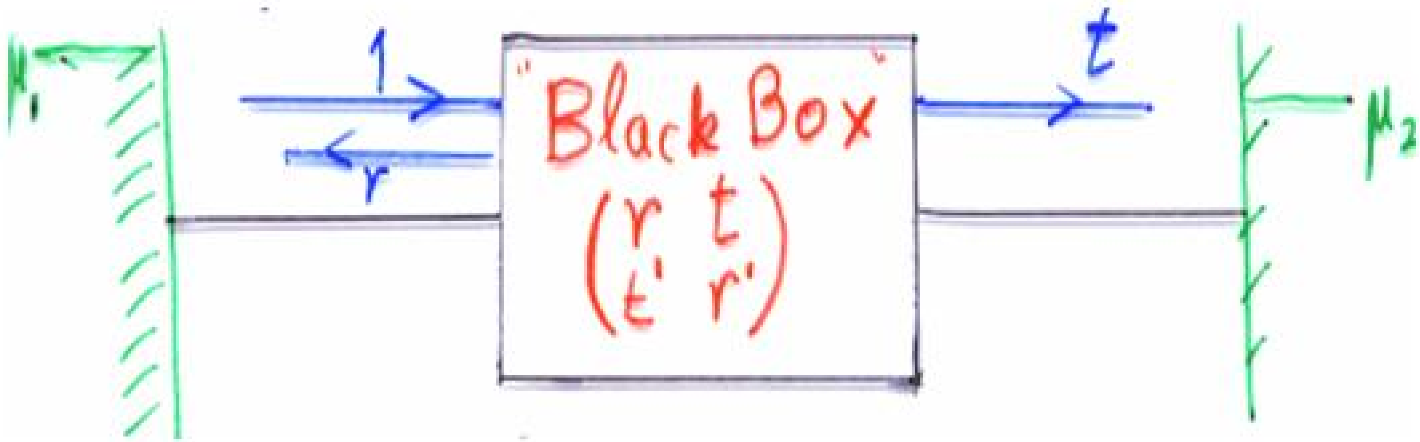
- **Need just a STEADY STATE SYSTEM:**

  Density-matrix diagonal in the energy representation.

  "States |i> with probabilities P_i , no coherencies"

- **P_i -- not necessarily thermal, T does not appear in this version of the FDT (only ω)!**

Landauer: 2-terminal conductance = transmission



$$G \equiv I/V = (e^2/\pi\hbar)\,|t|^2$$, with spin.

$$eV \equiv \mu_1 - \mu_2$$

Equilibrium Noise in the Landauer Picture

$$|j_{ll}|^2 = |j_{ll}|^2 = (evT)^2 \; ; \; |j_{lr}|^2 = |j_{rl}|^2 = (ev\,\mathrm{T}(1\text{-}\mathrm{T}))^2$$

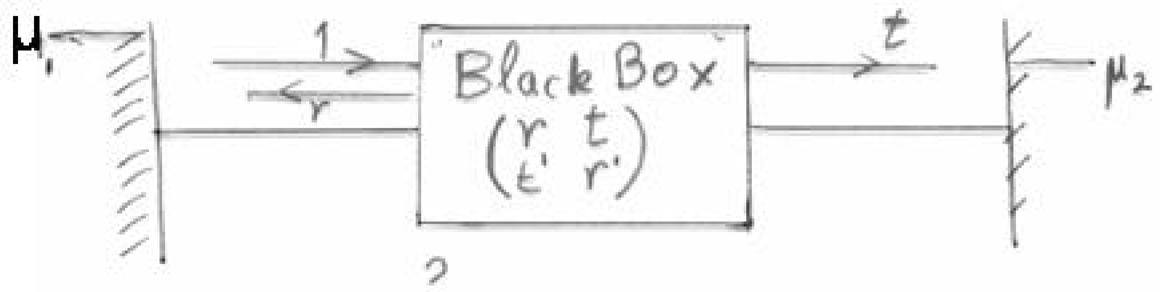
Since $\mathrm{T}(1-\mathrm{T}) + \mathrm{T}^2 = \mathrm{T}$, **from van Hove-type expression for** $S(\omega)$ **:**

- Temp = 0: **$S(\omega) \propto$ G ω, (ω < 0 only)**
- Temp >> **$\hbar\omega$: $S(\omega) \propto$ G** $\cdot$Temp.

(Nyquist!)

Quantum Shot-Noise (Khlus, Lesovik)

For Fermi–Sea Conductors, different for BEAMS in Vacuum, for same current.

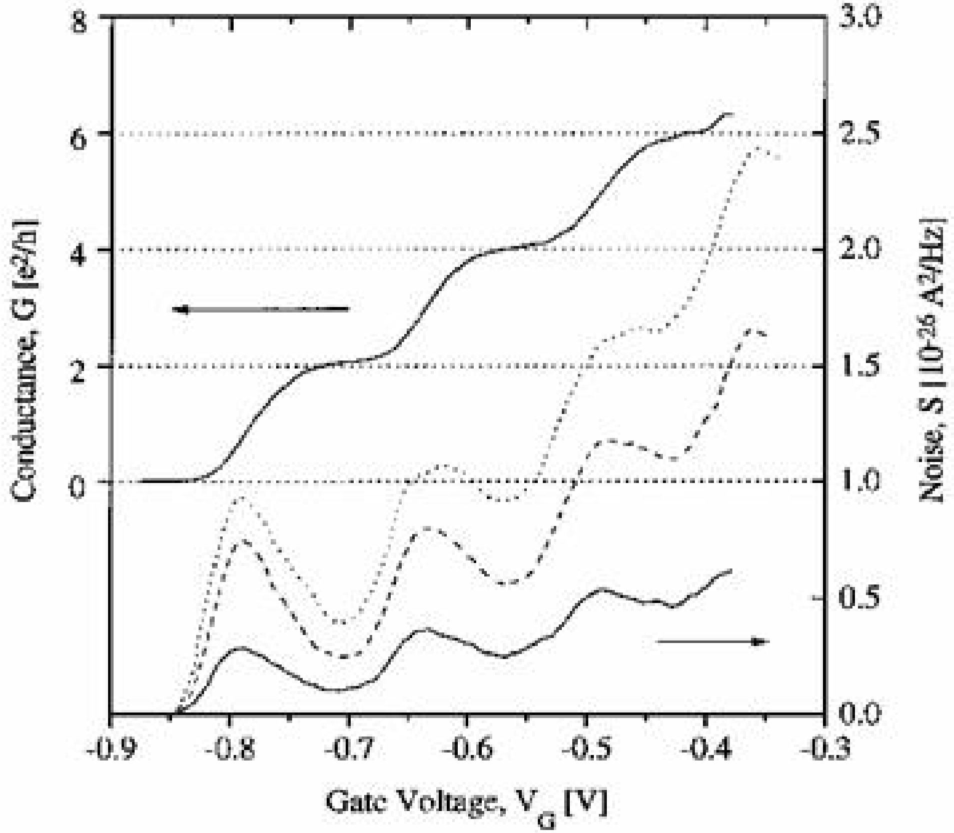


Left-coming Scattering state

$|\langle lk|\, j\, |rk'\rangle|^2 = v_F^2\ TR$, for ($k - k' \ll 1/L$)

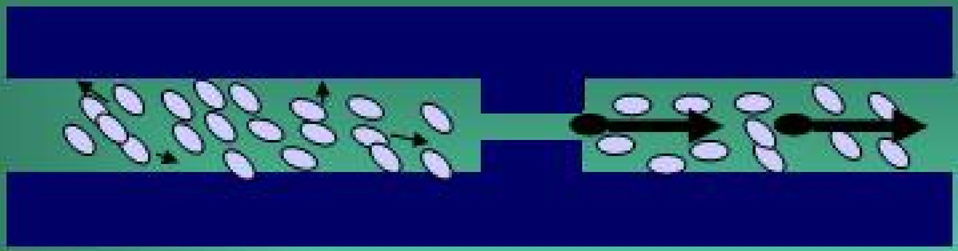
$\rightarrow S(\omega) = 2e(e^2V/\pi\hbar)\, T(1-T)$, $\omega \ll V$

$= 0$, $\omega > V$. This is Excess Noise.



Exp confirmation, of T(1-T)

Reznikov et al, WIS, 1997



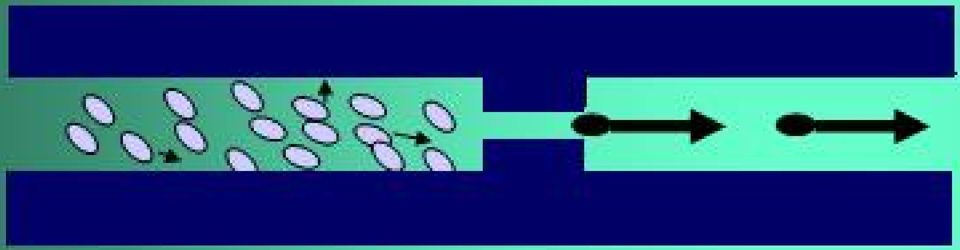
Current Noise Measurment in Quantum Point Contact

Shot noise measurment.

Pauli blocking effect between **all** particles.

Charge 1/3 detection (Weizmann – Saclay).

Interaction effects.



Current Noise Measurment in Beams in Vacuum.

Shot noise measurment.

Pauli blocking effect between the particles in the current **only**.

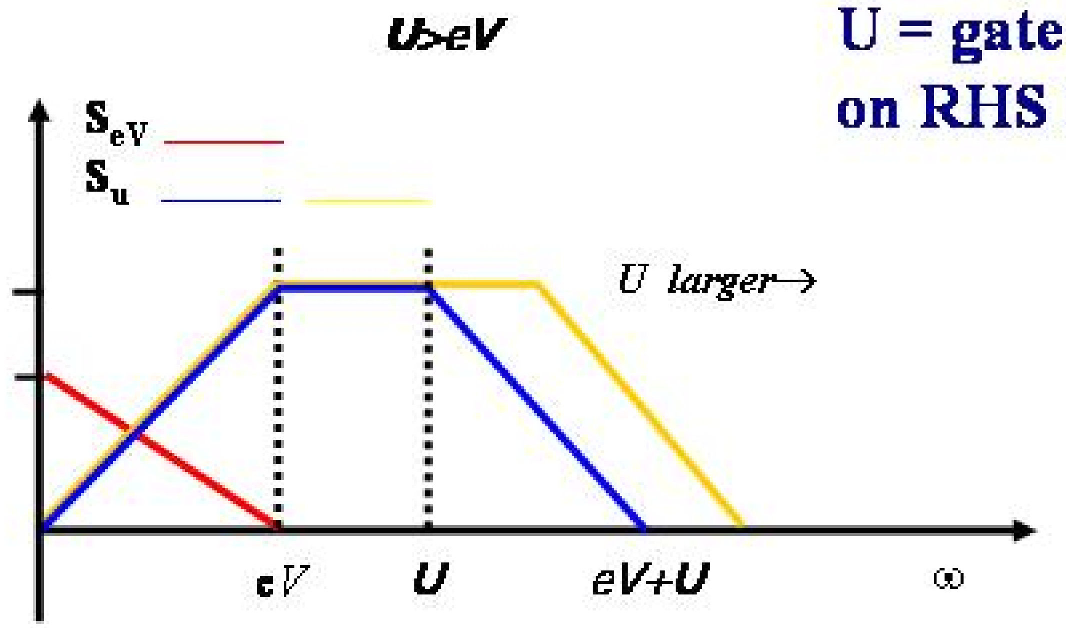
Charge 1/3 detection: impossible.

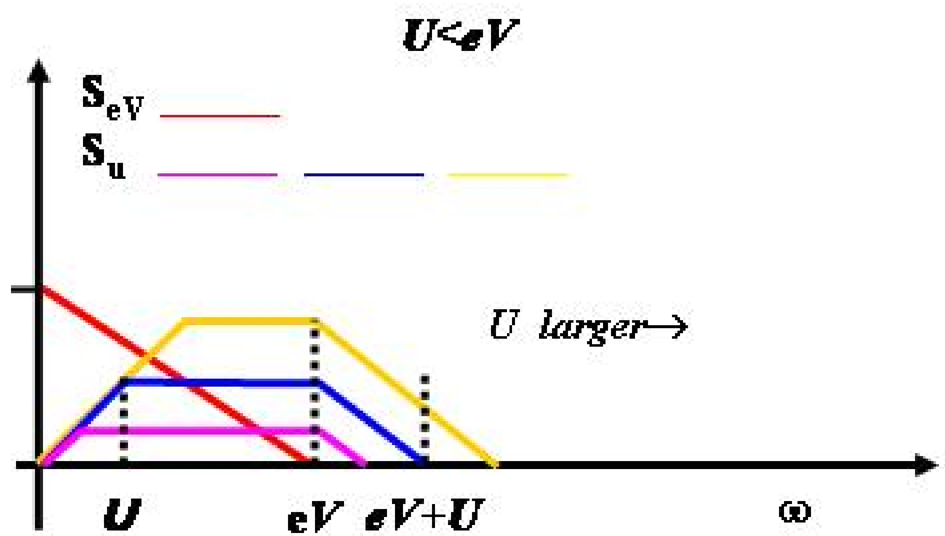
Interaction effects.

Is the current noise identical to a beam in vacuum?

Answer: NO. The Pauli principle blocks more transitions in the point-contact, so a different noise is emitted. By changing the occupancy at the sink (with a gate), this difference can be manipulated and the radiation spectrum can be controlled.

U = gate potential on RHS lead.





A recent motivation

How can we observe fractional charge (FQHE, superconductors) if current is collected in normal leads?

- **Do we really measure current fluctuations in normal leads?**

ANSWER: NO!!!

THE EM FIELDS ARE MEASURED.

(i.e. the radiation produced by I(t)!)

Partial Conclusions

- **The noise power is the ability of the system to emit/absorb (depending on sign of ω).**

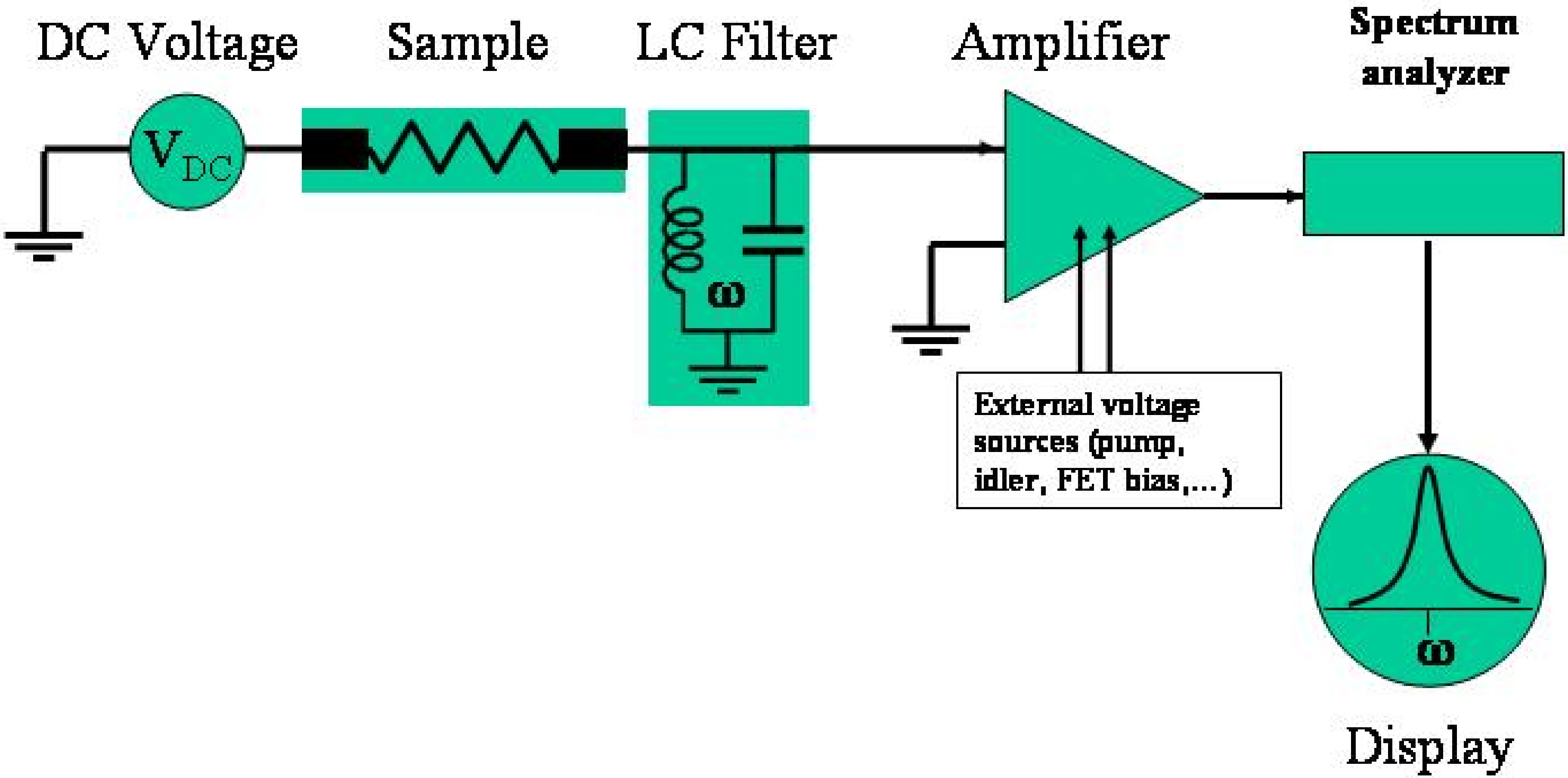
  FDT: NET absorption from classical field.

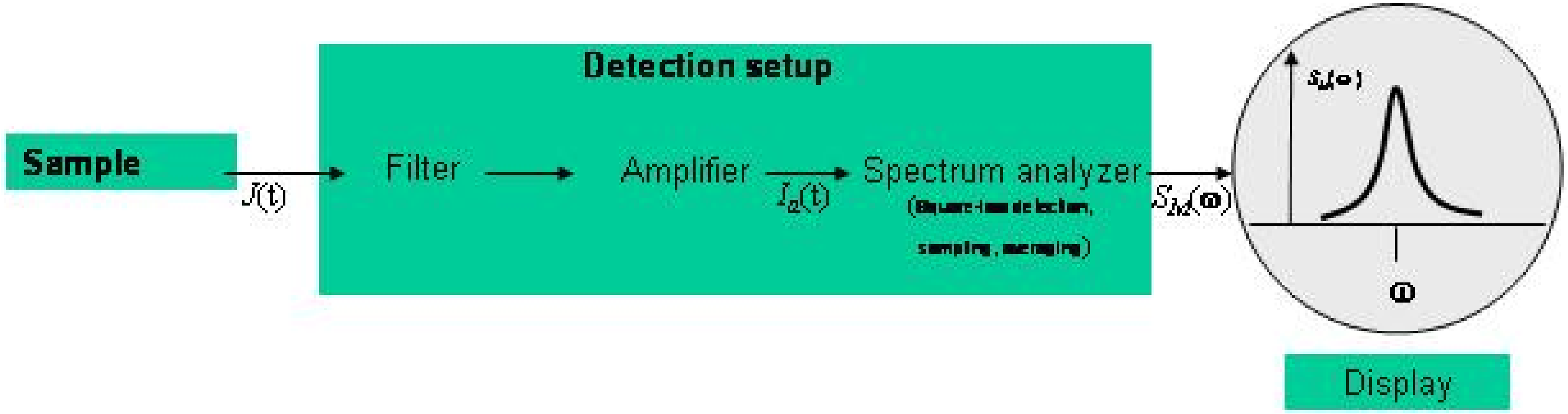
  (Valid also in steady nonequilibrium States)
- **Nothing is emitted from a T = 0 sample,**

  but it may absorb…
- **Noise power depends on final state filling.**
- **Exp confirmation: deBlock et al, PRL 2003.**

Full Noise Measurement Chain

Typical experimental setup:





Problem: Amp + Filter add their own stray noise to measured result,

NONUNIVERSAL!!!

Examples

A cooled and a warm linear Amplifier,
a phase sensitive or insensitive linear Amplifier
will give different results for $S_M(V,\omega)$.

These differences can be quantum mechanical.

WHAT ARE THE FUNDAMENTAL LIMITATIONS?

Yurke and Denker, PRA, '84

Simple Trick: Make an *Excess* Quantum

Noise Measurement

Nonuniversal portion cancels?

Measuring nonequilibrium quantum noise

- Problem. Other types of noise exist in the system. Thermal noise, amplifier noise, etc…

- Solution. Make an *excess* noise measurement:

1. Measure $S_M(V,\omega)$

   Turn on the voltage and make a noise measurement.

2. Measure $S_M(0,\omega)$

   Turn off the voltage and make another noise measurement.

3. Subtract the results.

$$S_{M,excess}(\omega) \equiv S_M(V,\omega) - S_M(0,\omega)$$

However, What about Excess Noise?

Can nonuniversal portion cancel?

It Does, in linear conductance regime!

This is our first main result

$$S_{M,excess}(V,\omega) = G^2 \times S_{excess}(V,\omega)$$

$$S(V,\omega) \equiv \int_{-\infty}^{\infty} dt e^{i\omega t} \left\langle \hat{J}_e(0) \hat{J}_e(t) \right\rangle$$

$G^2 = (\text{amplification})^2$

NO SYMMETRIZATION!!!

$$S_{M,excess}(V,\omega) = G \times S_{excess}(V,\omega)$$

Physical meaning of the result

$$S_{M,excess}(V,\omega) = G^2 \times S_{excess}(V,\omega)$$

What is obtained in an excess noise measurement is the excess ***power-flow*** from the sample into the detector. This is the reason for the universality of the result.

Filter and Amplifier strongly coupled to their baths

(=>Amplifier noise does not change with sample voltage)

$$S_M(\Omega) = G^2 \times < \Delta I_f^2 > / \Delta\Omega + S_N(\Omega)$$

$S_N(\Omega)$= Amp Noise (**independent of sample**)

Ω = Center filter frequency, L = its self-inductance

$\Delta\Omega$ = filter bandwidth, N_Ω = no of its quanta

$$< \Delta I_f^2 > / \quad L = \gamma^2 [S(\Omega) - 2N_\Omega \hbar\Omega \, G_D(\Omega)]$$

($\gamma \propto$ sample-filter coupling)

$G_D(\Omega)$ = differential sample conductance

When is it valid?

As long as differential conductance does not change – backflow into sample is

INDEPENDENT OF VOLTAGE

i.e. in linear conductance regime

(also necessary to keep impedance matching!)

How to verify the result?

- Make a high frequency measurement and change the amplifier type.

  High frequency is required to distinguish the nonsymmetrized and symmetrized correlators.

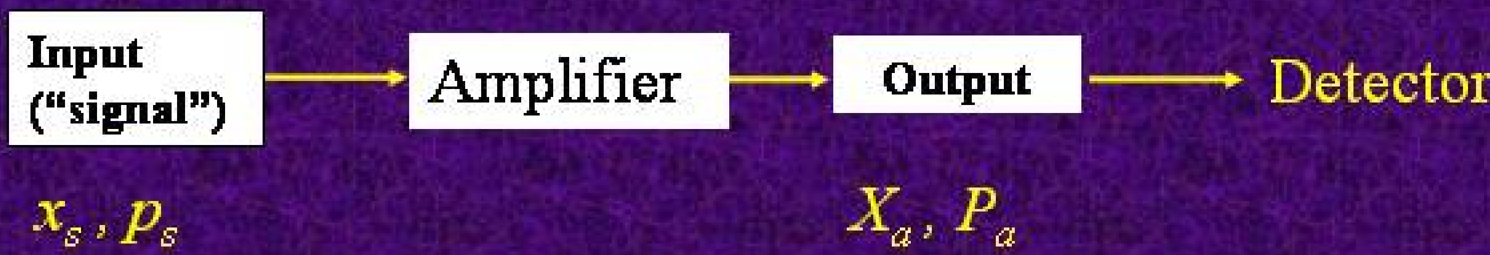
- Make a high frequency, $\omega \approx V$, measurement and change the amplifier temperature without changing the sample temperature.

Main Topic:

Fundamental Limitations
Imposed by the Heisenberg Principle on Noise and Back-Action in Nanoscopic Transistors.

Will use our generalized FDT for this!

A Linear Amplifier Must Add Noise
(E.g., C.M. Caves, 1979)



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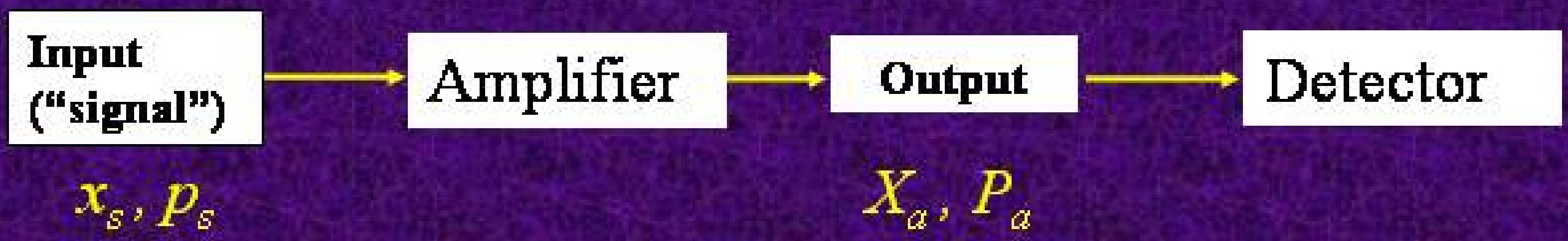

Linear Amplifier: $X_a = Gx_s\,, \quad P_a = Gp_s \quad G >> 1$

A Linear Amplifier Must Add Noise
(E.g., C.M. Caves, 1979)

Input ("signal") → Amplifier → Output → Detector

x_s, p_s $\qquad$ X_a, P_a

Linear Amplifier: $\quad X_a = Gx_s\,, \quad P_a = Gp_s \quad G >> 1$

But then $\quad [X_a, P_a] = i\hbar \;\Rightarrow\; [x_s, p_s] = \dfrac{i\hbar}{G^2} \;\Rightarrow\; \Delta x_s \Delta p_s = \dfrac{\hbar}{2G^2} < \dfrac{\hbar}{2}$

Heisenberg principle is violated.

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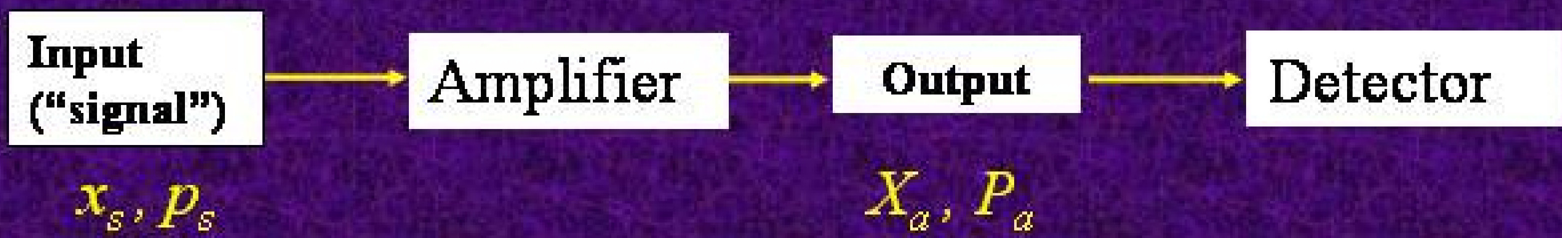

Linear Amplifier: $X_a = X_a = Gx_s\,, \quad P_a = Gp_s >> 1$

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Heisenberg principle is violated.

$\Rightarrow$ A Linear Amplifier does not exist !

A Linear Amplifier Must Add Noise
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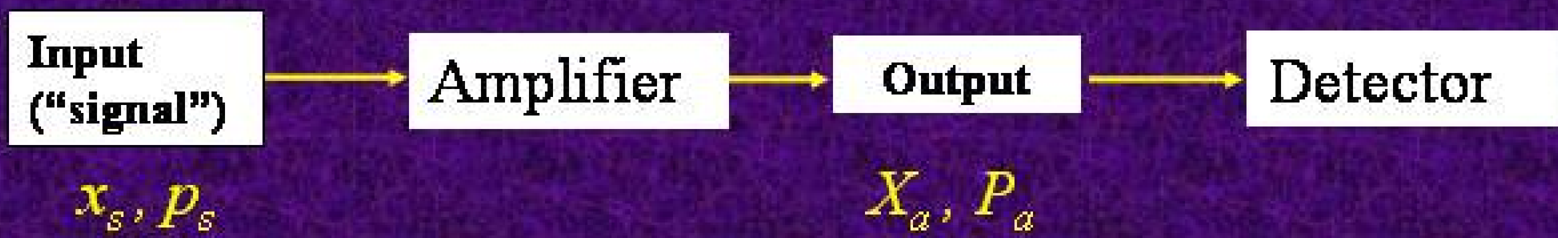
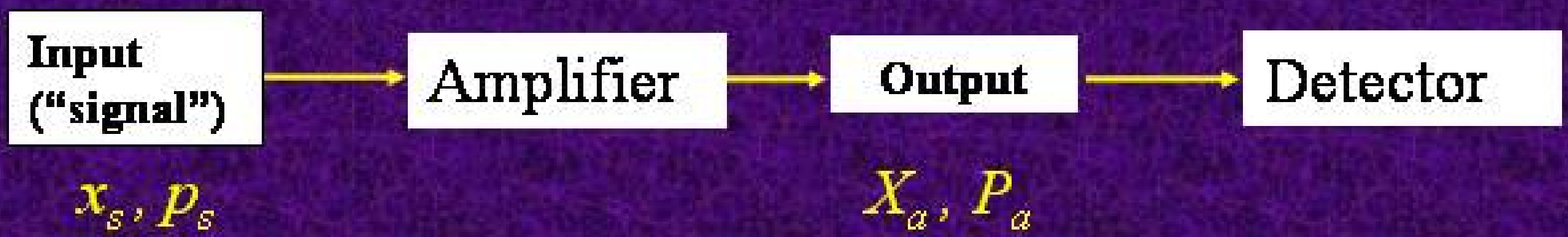


In order to keep the linear input-output relation, with a large gain, the amplifier must add noise

$$X_a = Gx_s + X_N, \quad P_a = Gp_s + P_N$$

A Linear Amplifier Must Add Noise
(E.g., C.M. Caves, 1979)



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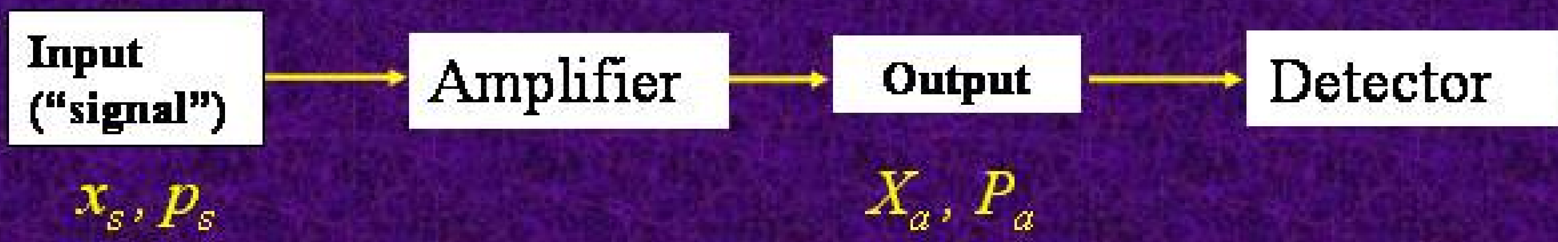
$$X_a = Gx_s + X_N, \quad P_a = Gp_s + P_N$$

choose $[X_N, P_N] = -(G^2 - 1)i\hbar$ $\quad X_N, P_N$ act on the amplifier state

then $\Rightarrow [X_a, P_a] = [X_N, P_N] + [x_s, p_s] = G^2 i\hbar - (G^2 - 1)i\hbar = i\hbar$

A Linear Amplifier Must Add Noise (E.g., C.M. Caves, 1979)



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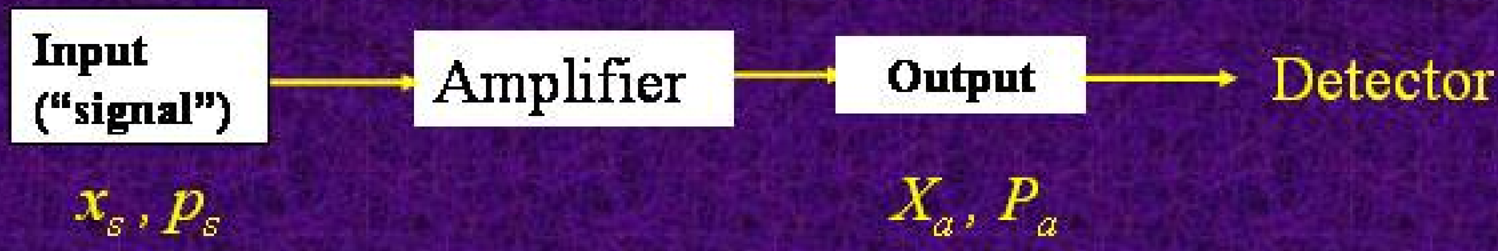
then $\Rightarrow [X_a, P_a] = [X_N, P_N] + [x_s, p_s] = G^2 i\hbar - (G^2 - 1)i\hbar = i\hbar$

Where do X_N and P_N come from? What is the noise source?

A Linear Amplifier Must Add Noise
(E.g., C.M. Caves, 1979)



Examples: x and p of an harmonic oscillator, or the positive-frequency and negative-frequency fourier component of a current.

x and p have simple c-number commutators. This is ***not*** *the case for the current componenets!* ***Have to consider their expectation values, using generalized Kubo.***

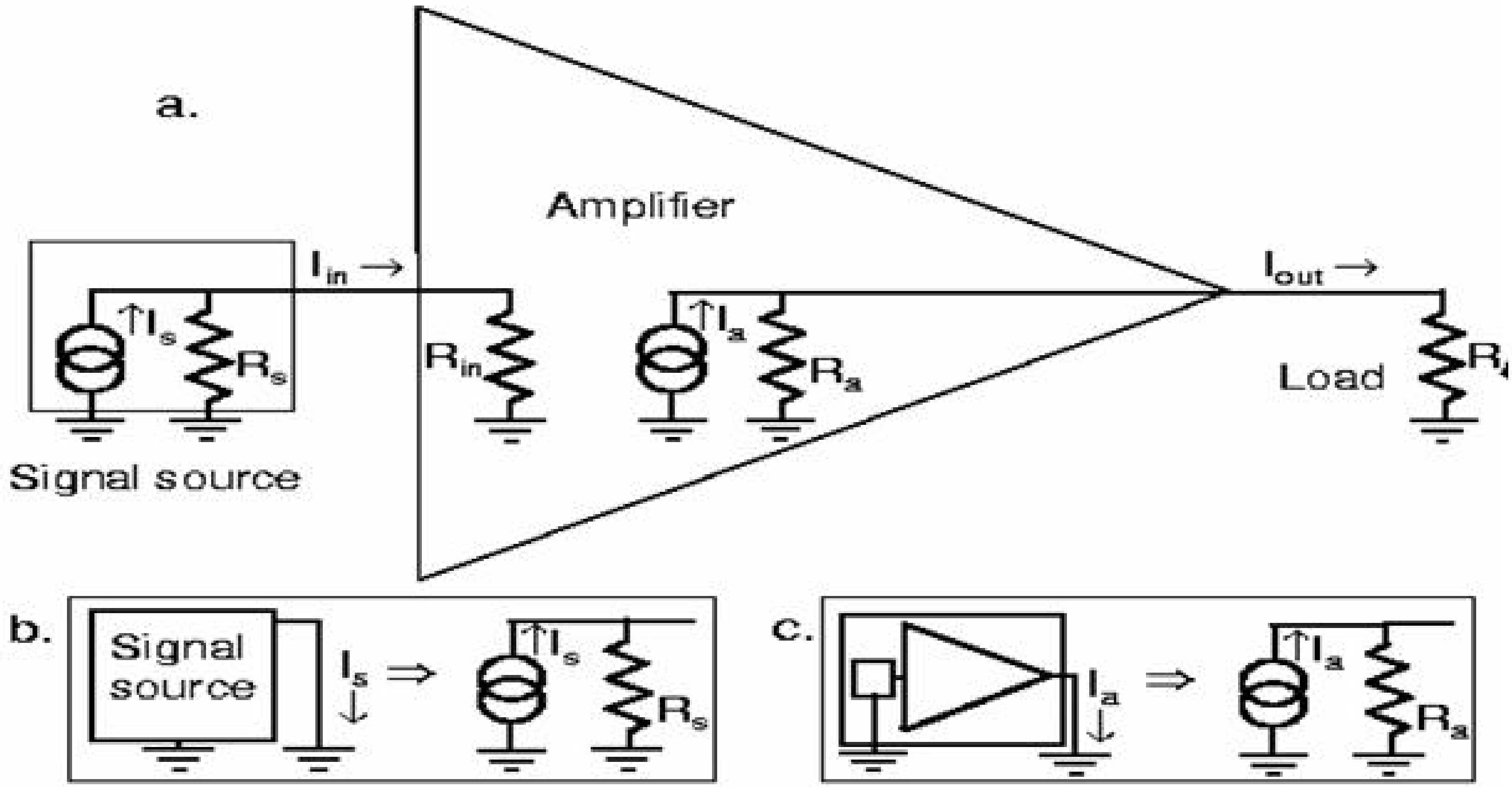
Cosine and sine components of any current Filtered with window-width $\Delta\omega$

$$I_c(t) = \frac{1}{\sqrt{2\pi}} \int_{-\Delta\omega/2}^{\Delta\omega/2} d\omega \; I(\omega_0 + \omega) e^{-i\omega t} + H.c.$$

and

$$I_s(t) = \frac{1}{\sqrt{2\pi}} \int_{-\Delta\omega/2}^{\Delta\omega/2} d\omega \; -iI(\omega_0 + \omega) e^{-i\omega t} + H.c. \; .$$

Scheme of Amplifier



This generalizes results on photonic amps, where the current commutators are c-numbers.

For phase insensitive linear amp:

$$I_{Lc}(t) = G\left(\frac{g_L}{g_S}\right)^{1/2} I_{Sc}(t) + I_{Nc}(t).$$

$$I_{Ls}(t) = G\left(\frac{g_L}{g_S}\right)^{1/2} I_{Ss}(t) + I_{Ns}(t) \; ..$$

g_L and g_S are load and signal conductances (matched to those of the amplifier). G^2 = power gain.

Our Generalized Kubo:

$$S(-\omega) - S(\omega) = 2\hbar\omega g \, ,$$

where g is the differential conductance, leads to:

$$\langle [I_c(t), I_s(t)] \rangle = 4i\hbar\omega_0 g \Delta\nu \ .$$

From our Kubo-based commutation rules:

$$\langle [I_{Ns}(t), I_{Nc}(t)] \rangle = 2i(G^2 - 1)\hbar\omega_0 g_L \Delta\nu \ .$$

Hence:

$$\Delta I_{Ns} \Delta I_{Nc} \geq (G^2 - 1)\hbar\omega_0 g_L \Delta\nu \ .$$

(See PRL **93**, 250601 (2004).)

Average noise-power delivered to the load

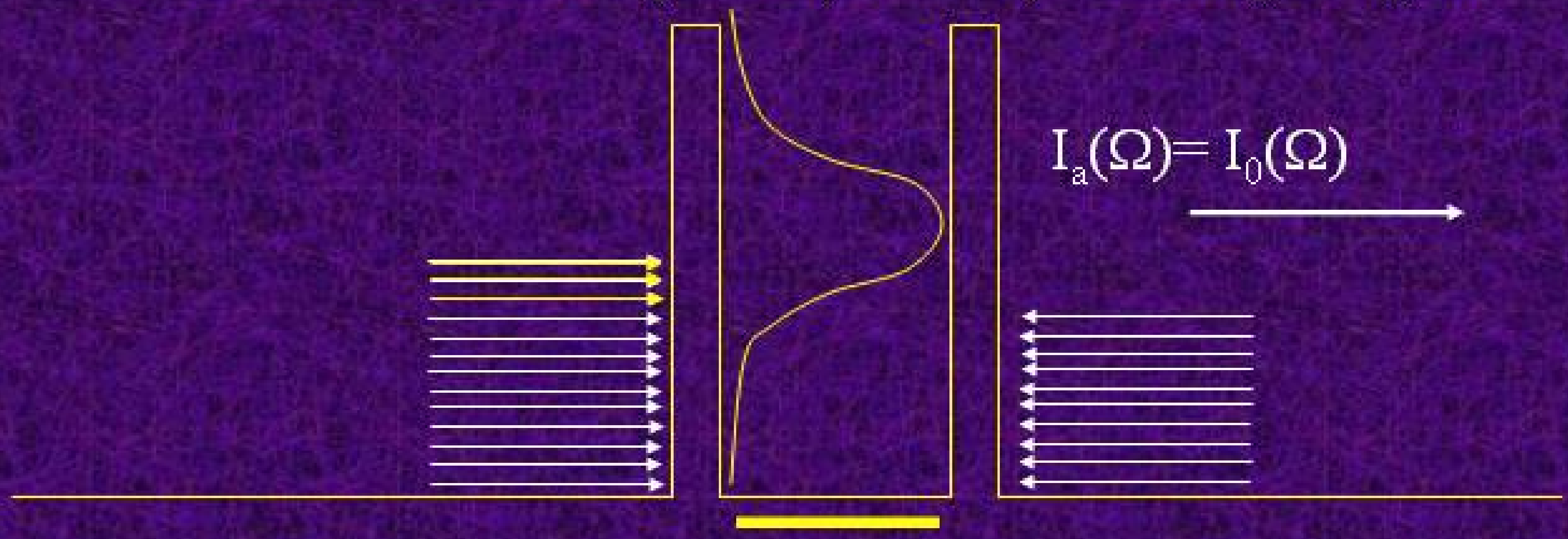
$$P_{LN} = \frac{1}{g_L}\langle I_N^2(t)\rangle = \frac{1}{2g_L}[\langle I_{Nc}^2\rangle + \langle I_{Ns}^2\rangle].$$

$$P_{LN} \geq \hbar\omega_0(G^2 - 1)\Delta\nu$$

(one-half in one direction)

A molecular or a mesoscopic amplifier

Resonant barrier coupled capacitively to an input signal



A molecular or a mesoscopic amplifier

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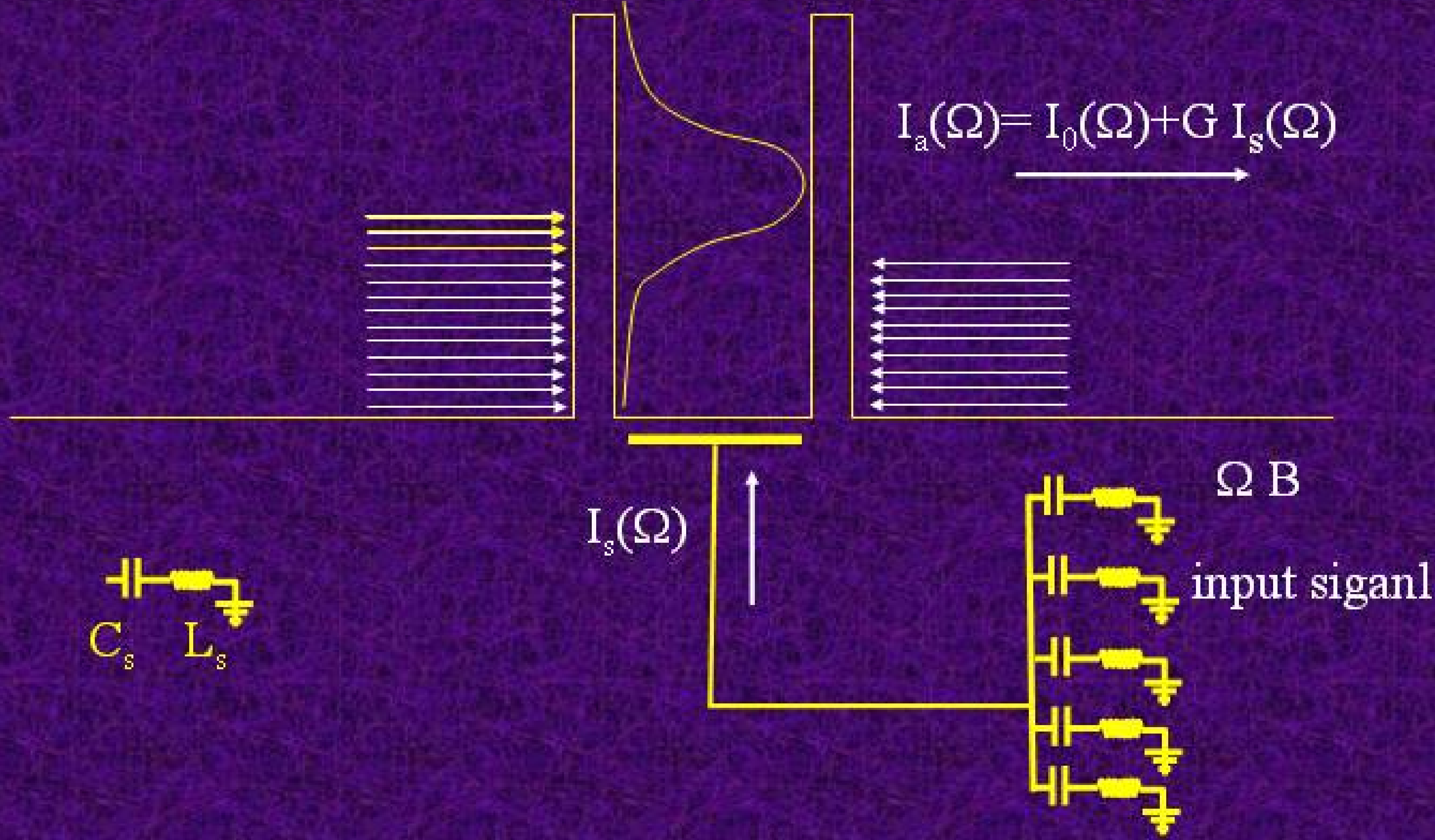


A molecular or a mesoscopic amplifier

Is $I_0(\Omega)$ enough to supply the necessary noise?

$$I_a(\Omega) = I_0(\Omega) + G\, I_s(\Omega) + \overset{?}{I_N}(\Omega)$$

A molecular or a mesoscopic amplifier

Is $I_0(\Omega)$ enough to supply the necessary noise? The expansion starts from the second term…

$$I_a(\Omega) = I_0(\Omega) + G\, I_s(\Omega) + \overset{?}{I_n}(\Omega)$$

$$G\, I_s(\Omega) \propto \gamma$$

$$I_N(\Omega) \propto \gamma^2$$

$\gamma \equiv$ cplg to signal

A molecular or a mesoscopic amplifier

Is $I_0(\Omega)$ enough to supply the necessary noise?

$$I_a(\Omega) = \overset{?}{I_0(\Omega)} + G\, I_s(\Omega) + I_n(\Omega)$$

$$G\, I_s(\Omega) \propto \gamma$$

$$I_N(\Omega) \propto \gamma^2$$

This question is important for a molecular or a mesoscopic amplifier because of two specific characteristics:

1. There is a current flowing even without coupling to the signal.

2. The amplified signal is proportional to the coupling (unlike most other quantum amplifiers)

Constraint on this amplifier:

$$\Delta I_0(t)\Delta I_n(t) \geq \frac{1}{4}G^2\hbar\omega_0 g_\ell \Delta\nu.$$

$$\sqrt{S_{00}S_{nn}} \geq G^2[S_{ss}(-\Omega)-S_{ss}(\Omega)]$$

Assumptions

•The amplifier is an a stationary state

• Small bandwidth

$$\Delta << \Omega$$

•Small coupling between the amplifier and the signal

$$\gamma = \frac{e\Delta Q_s}{C_g \boldsymbol{k}^2} << 1$$

• The correction to the (differential) conductivity of the amplifier due to the coupling with the signal is

$$G_{d,\gamma=0}^{amplifier} - G_{d,\gamma>0}^{amplifier} \propto \Delta$$

Amp noise summary

- Mesoscopic or molecular linear amplifiers must add noise to the signal to comply with Heisenberg principle.
- This noise is due to the original shot-noise, that is, before coupling to the signal, and the new one arising due to this coupling.
- Full analysis shows how to optimize these noises (PRL **96**, 133602 (2006)).

$$S_{M,excess}(V,\omega) = G \times S_{excess}(V,\omega)$$

Noise Conclusions

- Current noise measurement is setup dependent
- However, nonequilibrium excess noise can be setup independent since it basically measures the power flow from the sample into the detector.
- At T=0, An excess noise measurement yields the nonsymmetrized correlator, does not contain ZPF.
- Generalized FDT used to get constraints on amps'
- Since power, not accumulated charge, is measured → can get fractional charges in spite of leads!
- Amplification process gives **inherent noise**

Review of Decoherence
(mainly with mesoscopic Physics examples)

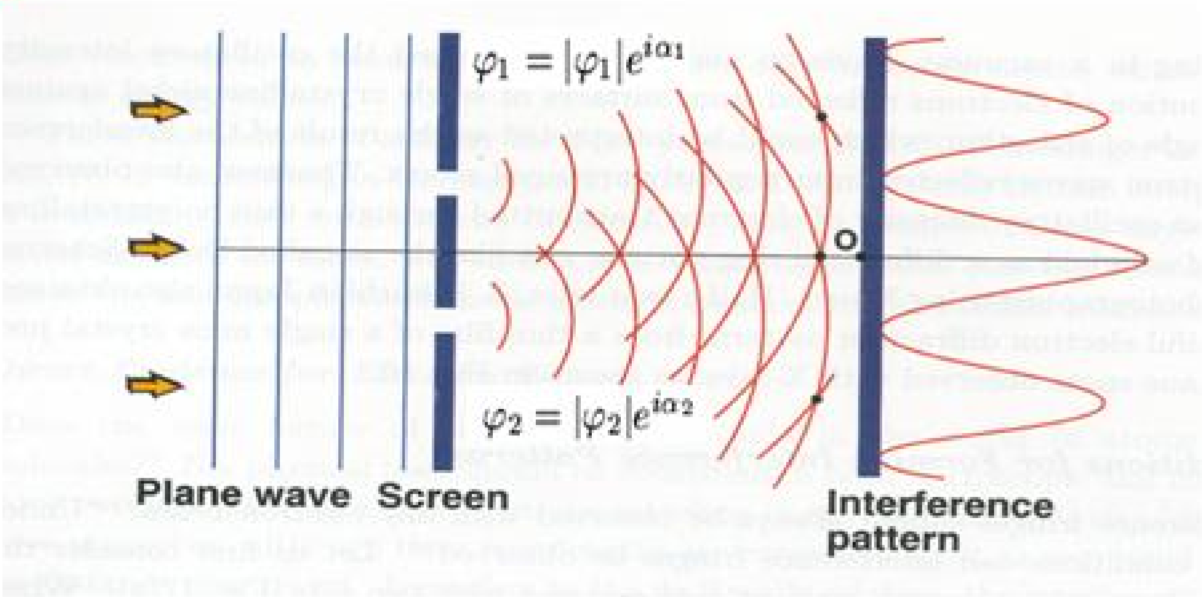
Yoseph Imry

the Weizmann Institute

OUTLINE OF DECOHERENCE

- Interference -- basics of wave physics (Q.M.), examples
- What destroys it? "Decoherence = Inelasticity - change of state of environment = which-path detection = interaction with environment fluctuations
- Some Physical remarks
- Disordered conductors -- especially low dimensions.
- Nonequilibrium dephasing by "quantum detector".
- Low-temperature limit ???
- Questions

Two-slit interference--a quintessential QM example:

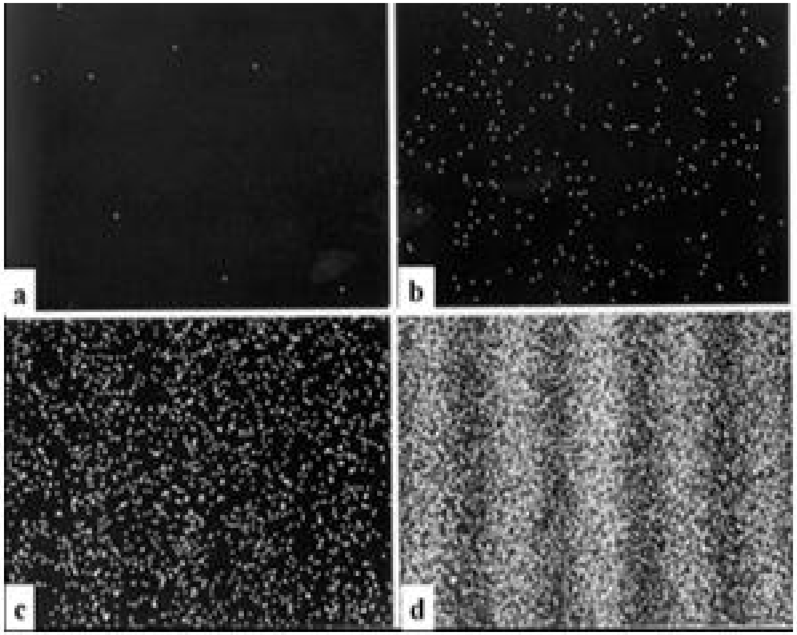


$$\varphi_1 = |\varphi_1| e^{i\alpha_1}, \quad \varphi_2 = |\varphi_2| e^{i\alpha_2}$$

$$P_{12} = |\varphi_1 + \varphi_2|^2 = |\varphi_1|^2 + |\varphi_2|^2 + 2|\varphi_1||\varphi_2| \underline{\cos(\alpha_1 - \alpha_2)}$$

"Two slit formula"

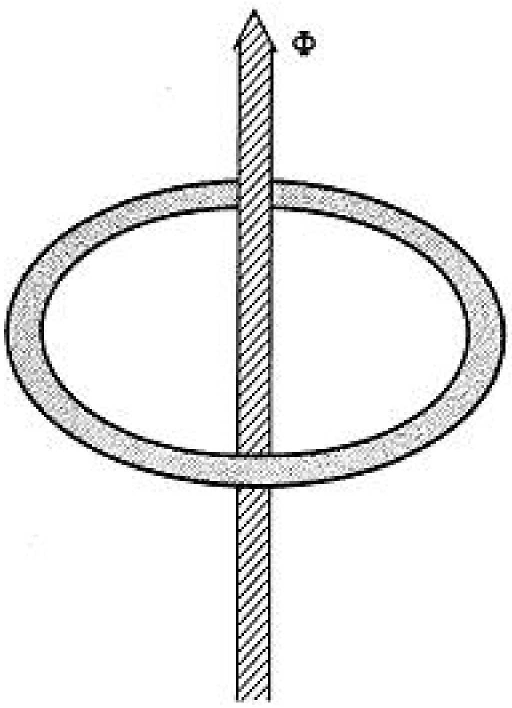
A. Tonomura: **Electron phase microscopy**

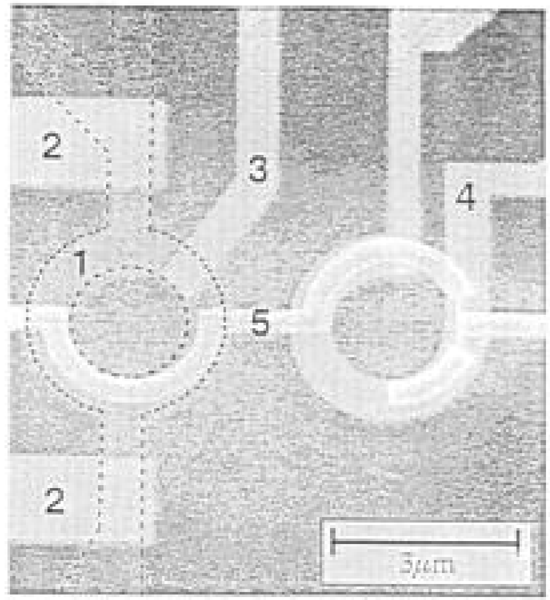


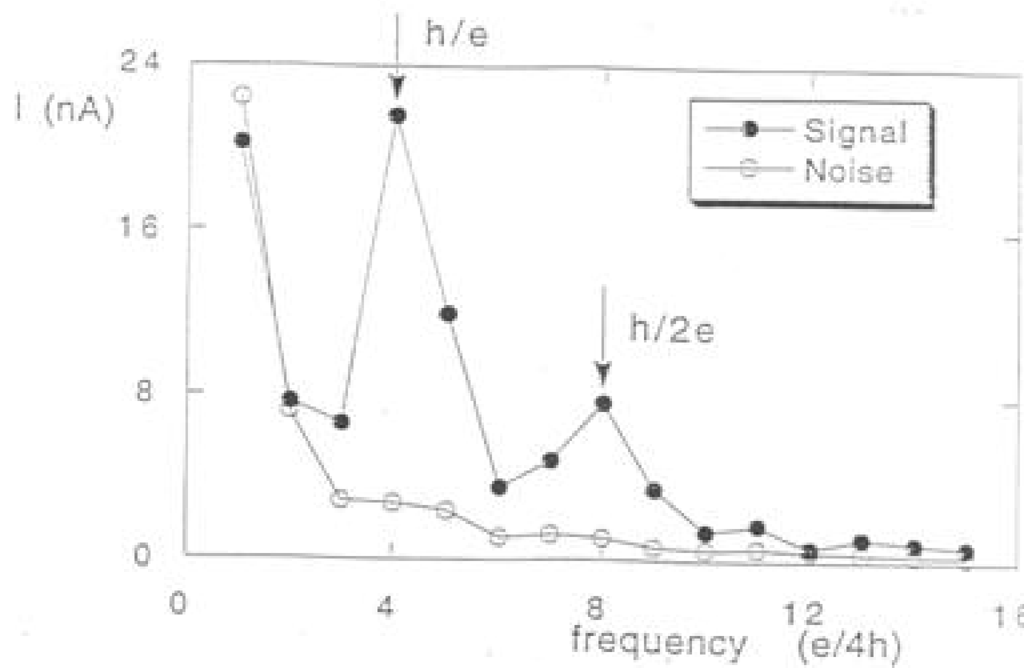
Each electron produces a seemingly random spot, but: Single electron events build up to from an interference pattern in the double-slit experiments.

A-B Flux in an isolated ring

- A-B flux equivalent to boundary condition.
- Physics periodic in flux, period h/e (*Byers-Yang*).
- "Persistent currents" exist due to flux.
- They do **not** decay by impurity scattering (*BIL*).




2
3
4
1
5
2
5μm


h/e
h/2e
I (nA)
24
16
8
0
Signal
Noise
0
4
8
12
16
frequency (e/4h)

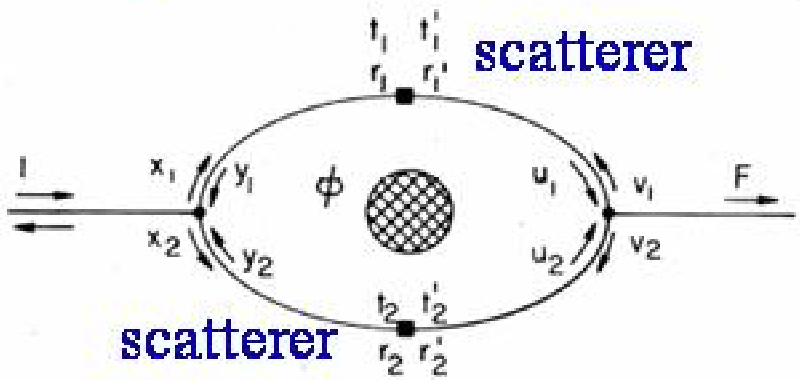
Quantum Oscillations and the Aharonov-Bohm Effect for Parallel Resistors

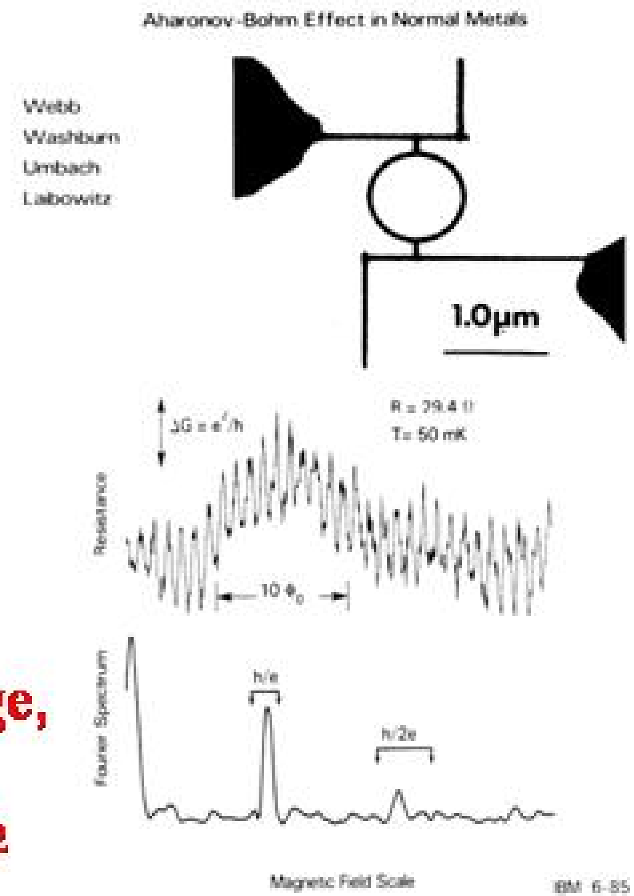
Yuval Gefen and Yoseph Imry
Department of Physics and Astronomy, Tel Aviv University, Tel Aviv 69978, Israel

and

M. Ya. Azbel[a]
IBM Research Center, Yorktown Heights, New York 10598
(Received 14 March 1983)

Closed system!





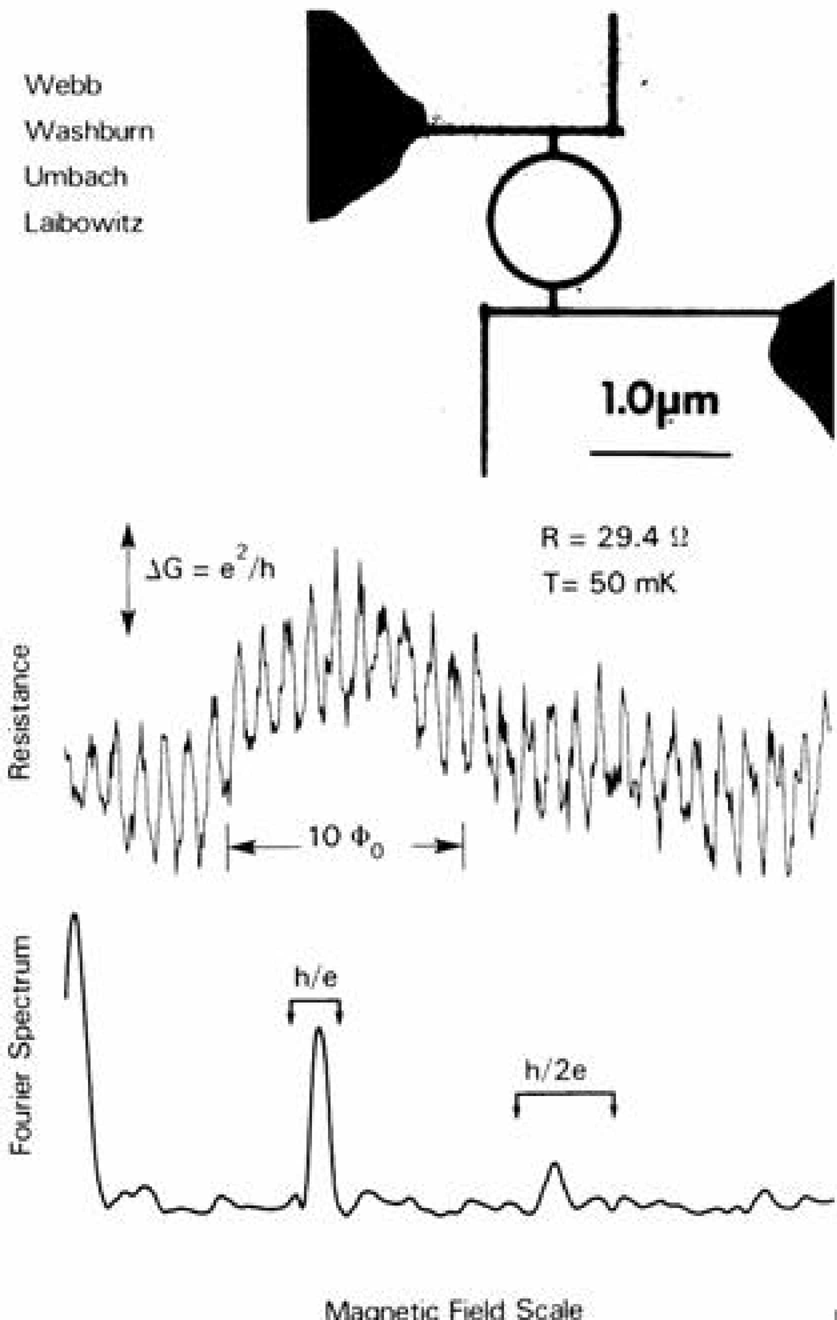
h/e osc. –mesoscopic fluctuation.

Compare:

h/2e osc. – impurity-ensemble average,

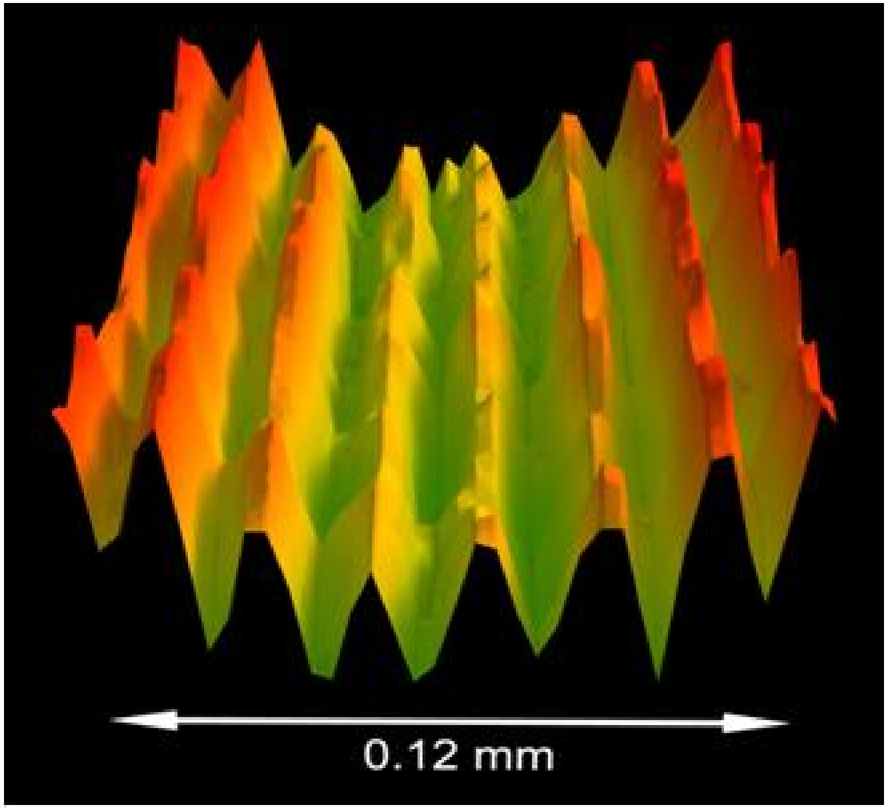
Altshuler, Aronov, Spivak, Sharvin[2]

Aharonov-Bohm Effect in Normal Metals



IBM 6-85

Matter-wave interference (Ketterle’s group)



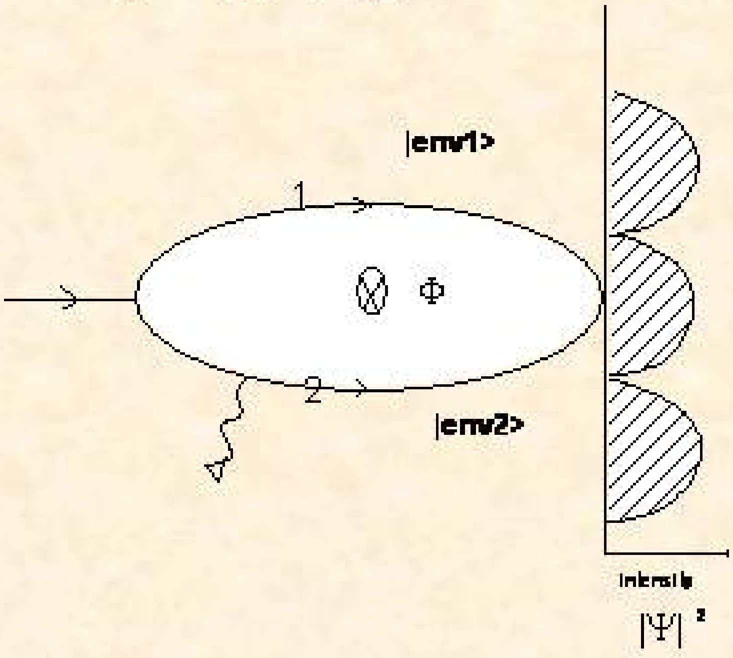
Interference of two expanding, overlapping BEC’s, which started as independent

"Decoherence", by environment

(via cplg to all other degrees of freedom)

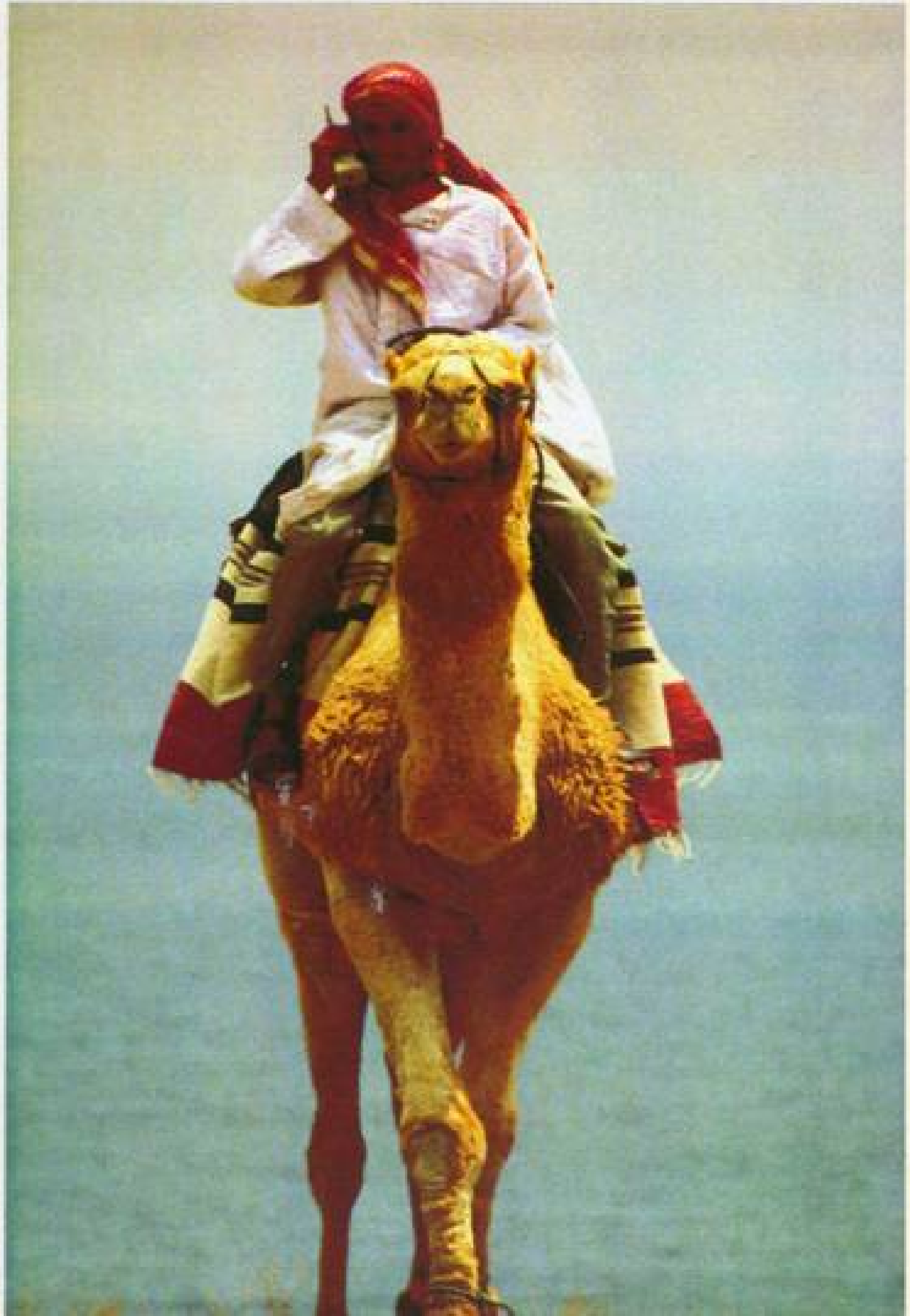
Two-wave interference

$\Psi = \Psi_1 + \Psi_2$



- What spoils the $2\mathrm{Re}(\Psi_1 \Psi_2^*)$ interference?
- ❖ Leaving a ("which path") trace in the environment : <env1|env2> = 0
- ❖ Inducing uncertainty in the relative phase,

  $\arg(\Psi_1 \Psi_2^*)$



Electromagnetic

Coupling to other

degrees of freedom

This is what

charged Particles

always do!!!

ΔΔ

These two statements are **exactly** equivalent (SAI, 89)

Proof: by considering the time evolution operator,

$\Delta\phi^2 = O(1) \Leftrightarrow$ **<env1|env2>~0**

$U = T \exp[-(1/\hbar)\int^t H_I(t')\, dt']$

- U induces changes in the environment state
- *and* creates an **uncertainty** in the phase, $\phi = \arg(\Psi_1 \Psi_2^*)$
- determined by the dynamic correlators of $H_I(t)$.

FLUCTUATION-DISSIPATION

THEOREM (FDT)

Physical Remarks

- **No dephasing if identical excitation is produced by 2 paths.**
- **How much energy transferred is irrelevant! (once transition has occurred).**
- **Excitation should resolve the 2 paths:**

  $$\mathbf{k} \cdot (\mathbf{x}_1 - \mathbf{x}_2) \sim \pi$$

- **Reabsorbing the excitation restores the phase.**
- **But: After interaction is switched off, env't becomes irrelevant.**
- **Special effects: Retrieval of interference by measurements on env't.**

  (epr, Stern, Hackenbroich &Weidenmuller)

$1/\tau_\phi$ ~ rate for particle to excite environment (and lose phase!)

Probability to excite the environment till time t, for a particle moving in medium, can be calculated via the

Fermi Golden Rule

Results produce all known cases (dirty metals, any d)

$$\Rightarrow 1/\tau_\phi = \int dq \int d\omega\, |V_q|^2$$

$$S_p(-q, -\omega) \cdot S_s(q, \omega).$$

⇑ particle ⇑ env.

S (q, ω)=dynamic structure factor=
F.T [density-density corr. Fcn]
Measures the corr. of space-time density fluctuations ⇒ much physical info. Known for models.
(see later…)

Agreement (of AAK results) with experiments:

Narrow wire ("quasi 1D"):

$$1/\tau_\phi \sim T^{2/3}$$

Very nontrivial (FLT???)

What does exp say?

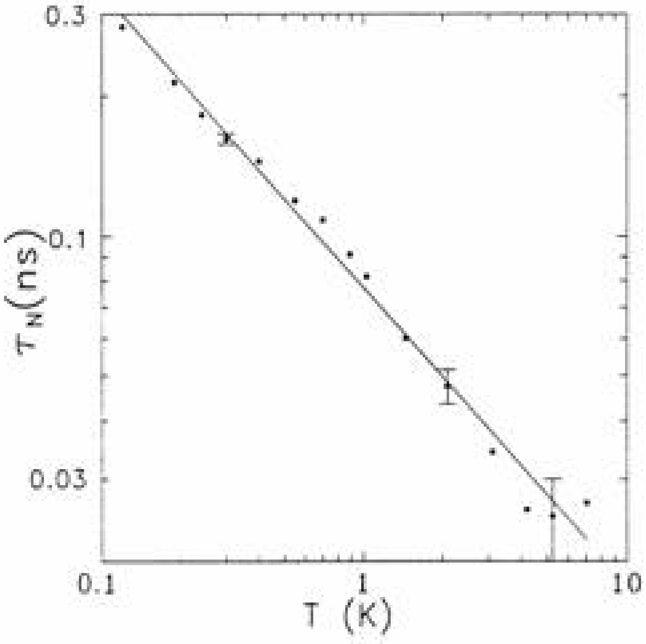
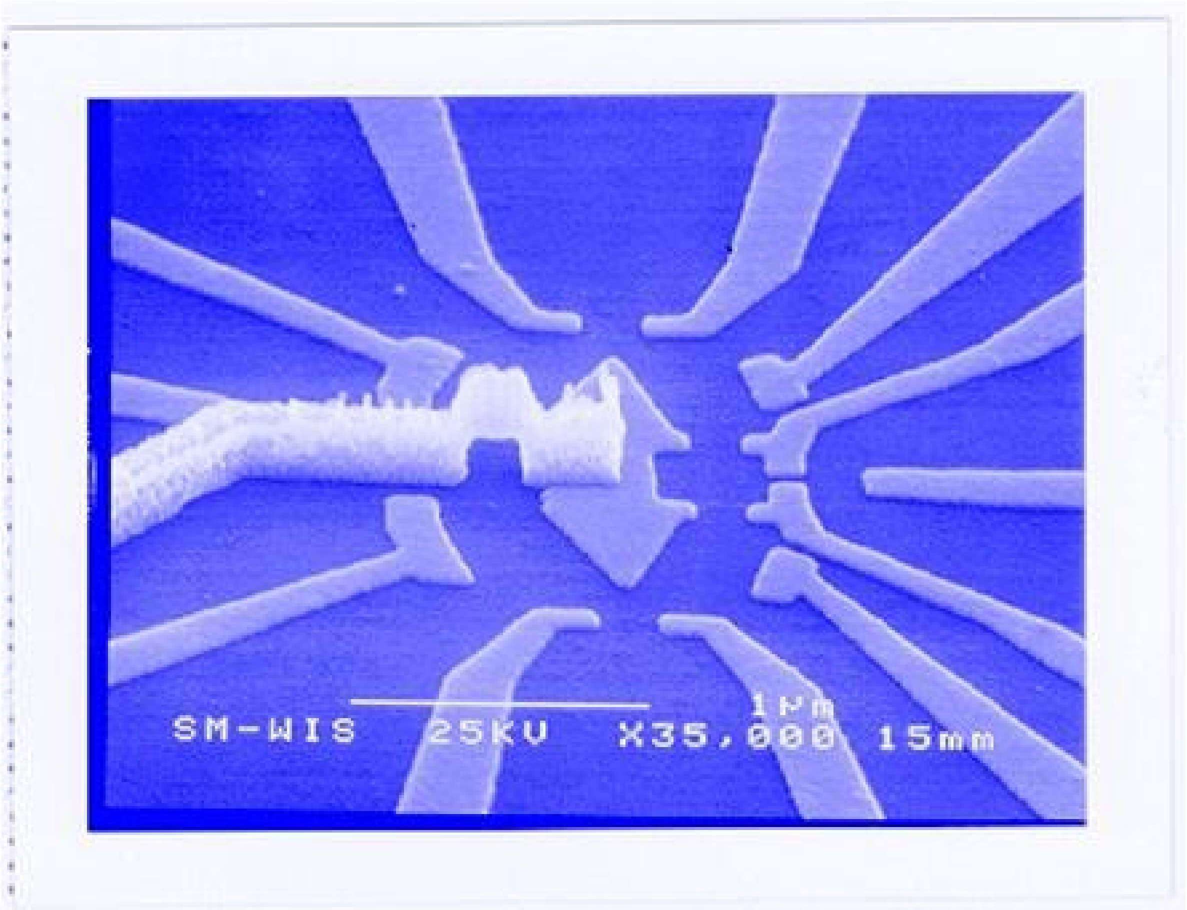


FIG. 2. Temperature dependence of τ_N. The solid line is the best power-law fit $\tau_N = 7.7\times10^{-11}$ (T/K)$^{-0.64}$.

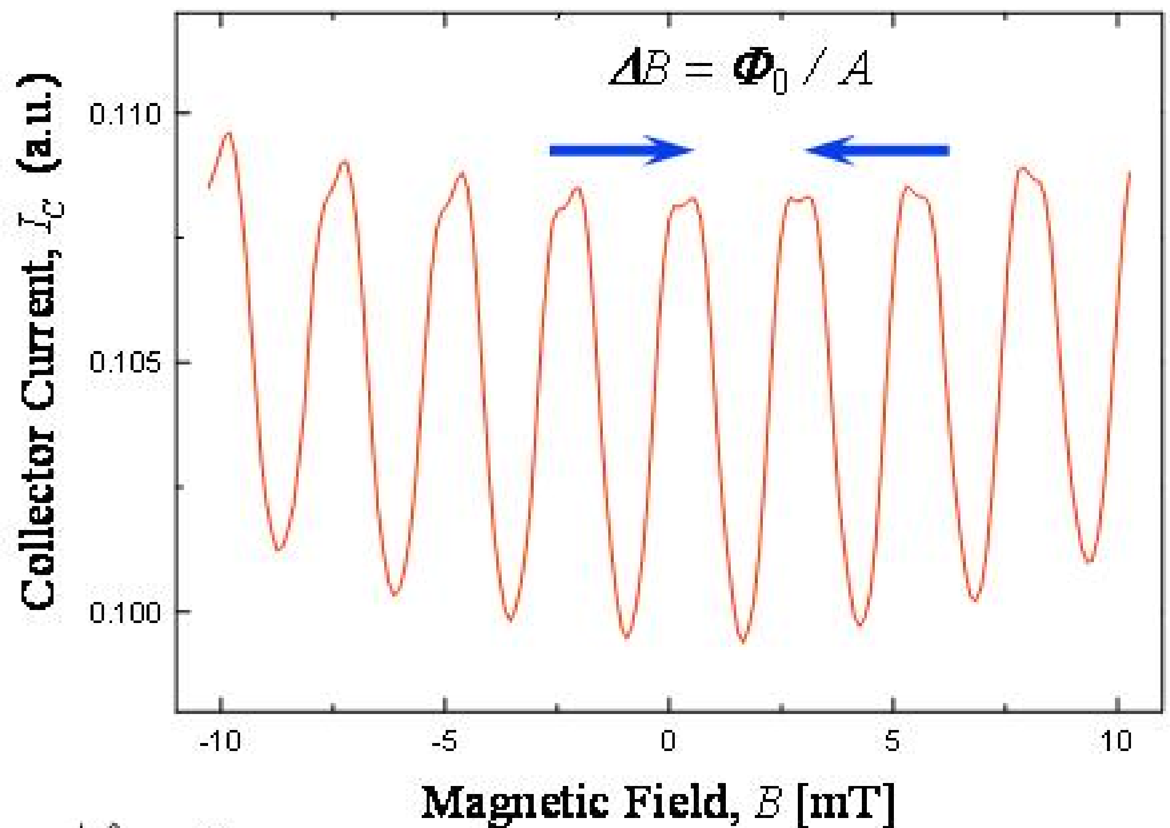
Controlled Decoherence

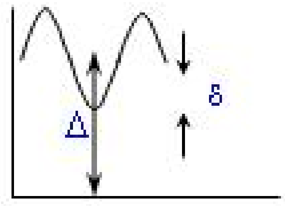
Buks et al.



Aharonov Bohm Oscillation

Effect of Which-path detection on visibility Of interference





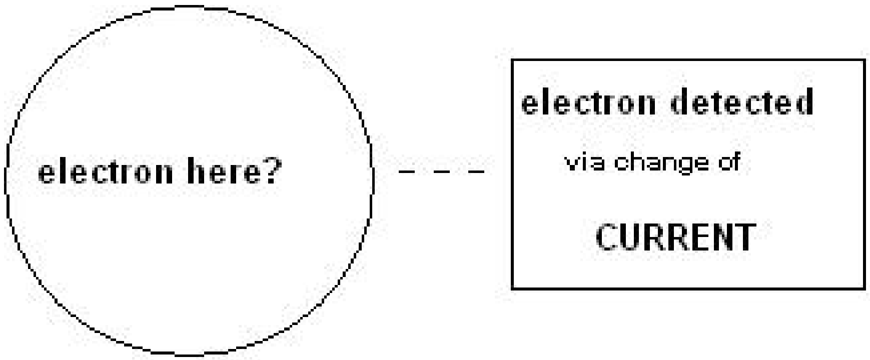
Visibility = δ/Δ

Nonequilibrium controlled decoherence

- No FDT out of equilibrium

- Purely Quantum-Mechanical Detector : Quantum point contact (QPC).

NO CLASSICAL OBSERVERS, etc...



Buks et al; Theory: Aleiner, Meir & Wingreen, Levinson…

Calc of τ_ϕ (for dephasing τ_ϕ ~ dwell time)

τ_ϕ is the time through which the shot-noise of the detector current is ~ its mean change via ΔT due to electron in dot:

$$\frac{1}{\tau_\varphi} = \frac{eV(\Delta T)^2}{8\pi\hbar T(1-T)}$$

Obtained from:

- **Orthogonality induced in detector state (Buks et al).**
- **Real transitions induced in the detector (Aleiner et al).**
- **Noise induced by detector on electron in dot (Levinson).**

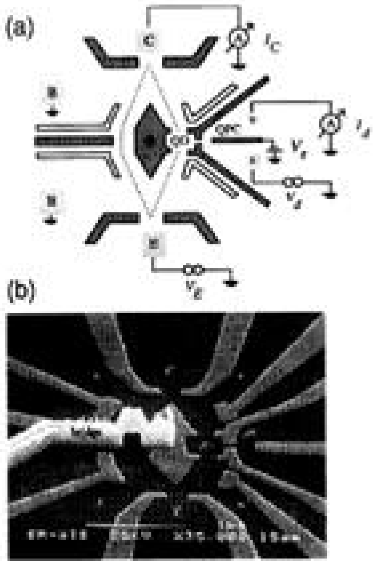


Figure 1: (a) A schematic description of the top electrodes and contacts of the interferometer and the detector. The interferometer is composed of three different regions, emitter E, collector C, and base regions B on both sides of the barrier with the two slits. The right slit is in a form of a QD (with area $0.4\times0.4\ \mu m^2$) with a QPC on its right side serving as a WP detector. (b) A top view SEM micrograph of the device. The gray areas are metallic gates deposited on the surface of the heterostructure. A special lithographic technique, involving a metallic air bridge, is used to contact the central gate that depletes the area between the two slits (serves also as plunger gate of the QD).

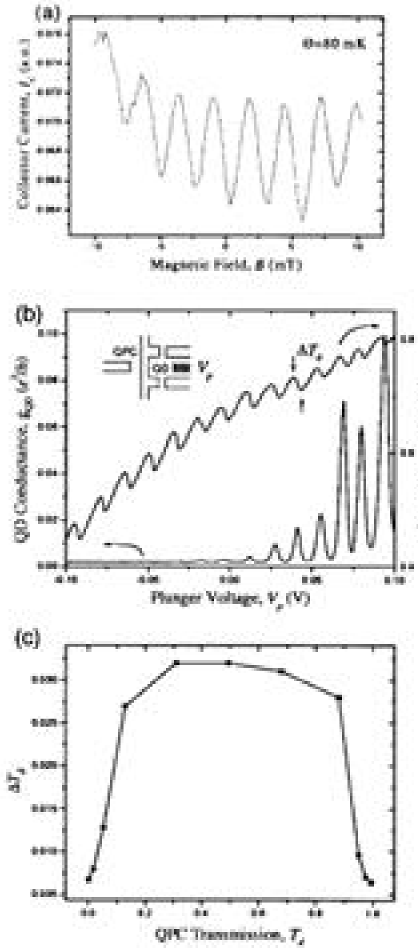


Figure 2: (a) AB oscillations in the collector current. (b) The conductance of the QD and that of the QPC detector as a function of the plunger gate voltage, V_p. The inset shows schematically the coupled structure. (c) The measured induced average change in the transmission probability of the QPC detector, ΔT_d, due to charging the QD as a function of T_d.

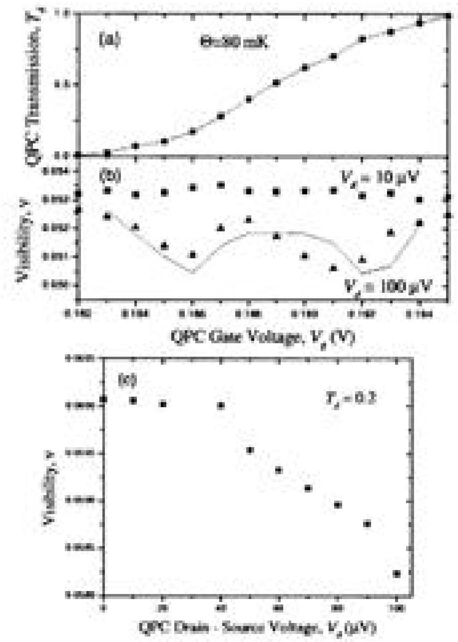


Figure 3: (a) The transmission probability of the QPC detector, T_d, as a function of the voltage applied to the right gate of the QPC detector, V_g. (b) The visibility of the AB oscillations as a function of V_g for two values of the drain source voltage across the detector, V_d. (c) The visibility of the AB oscillations as a function of V_d for a fixed $T_d = 0.2$.

LOW-TEMP SATURATION OF τ_ϕ ?

Mohanty, Jariwala and Webb (1997) and many others.

- Must rule out: EXTERNAL NOISE, MAGNETIC IMPURITIES, heating...
- DISAGREES WITH USUAL THEORY! ???
- Debye-Waller-type phenomenon?
- Unexpected low-energy excitations?
- Nonequilibrium effect?

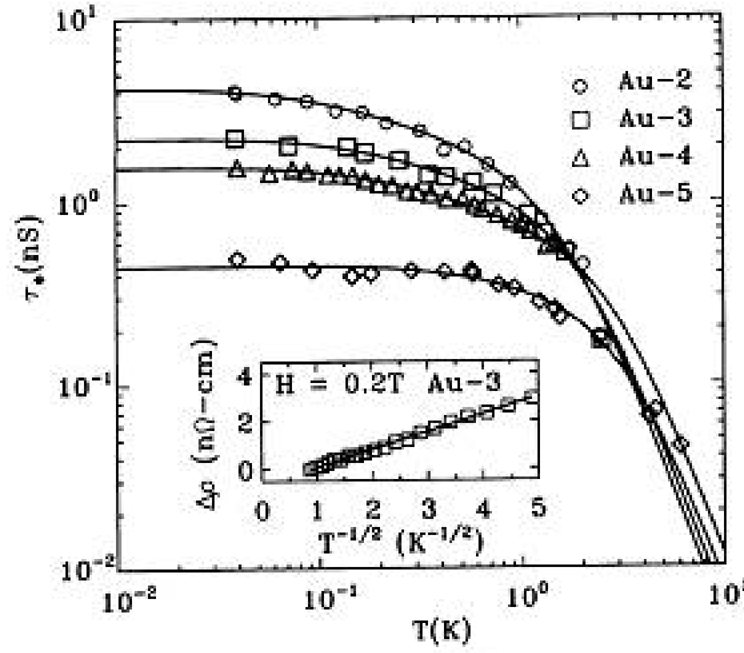


FIG. 2. Temperature dependence of τ_ϕ for four Au wires. Solid lines are fits to Eq. (1) with phonons. The inset is the EE contribution to $\Delta\rho$ with the theoretical prediction.

No Dephasing as $T \longrightarrow 0$!

Starting from our expression:

$$1/\tau_\phi = \int dq \int d\omega \, |V_q|^2$$

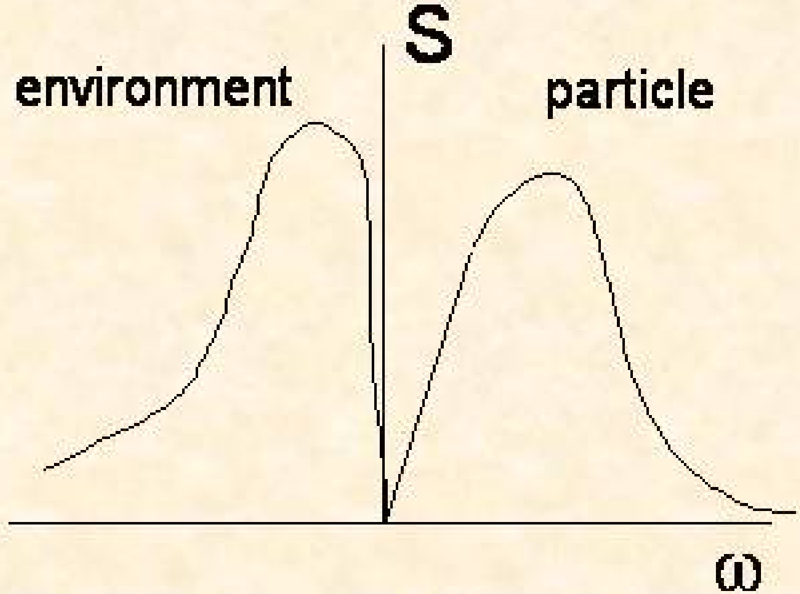
$$S_p(-q, -\omega) \cdot S_s(q, \omega),$$

we see that supports of two S's DO NOT OVERLAP $\Rightarrow \int = 0$.

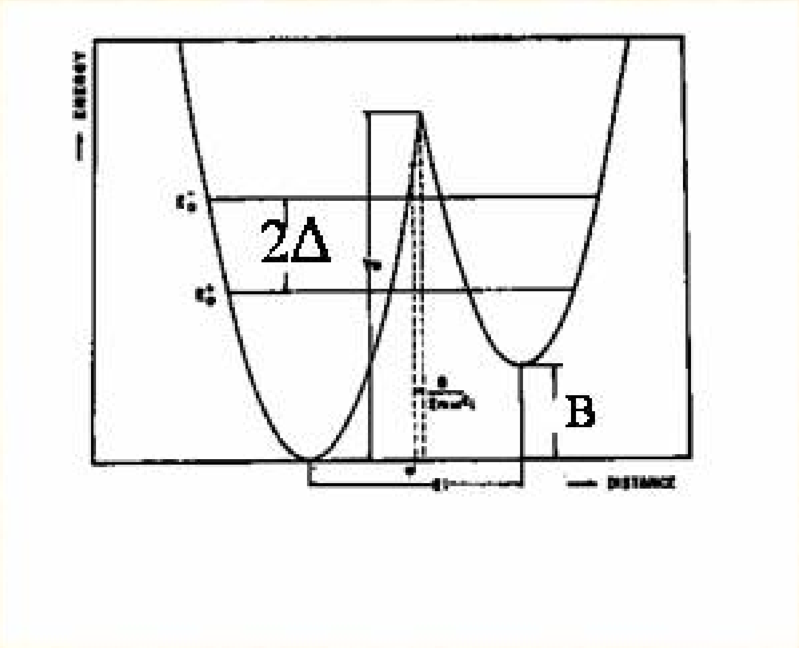
<u>Unless $\exists$ g.s. degeneracy</u>

(e.g. spins, disordered and unscreened!).

$T \longrightarrow 0$ deph ruled out by laws of thermodynamics!



What can cause apparent saturation of true $1/\tau_\phi$?
Need abundance of "soft" low-energy modes



$$2\Delta = 2\sqrt{\Omega_0^2 + B^2}.$$

- Can be **magnetic impurities**,
- Or (YI, Fukuyama, Schwab, 99)
  Two-level systems (TLS),
  as suggested by Anderson, Halperin and Varma for the low-T properties of glasses.
  Should exist due to disorder!
- In both cases, $1/\tau_\phi$ will vanish when $T \longrightarrow 0$.

Proper distribution of B and Ω_0 can explain apparent saturation

Experiment: T⟶ 0 deph is an interesting artifact

Pierre et al, 2003,
Magnetic impurities in the metal. (ppm level)

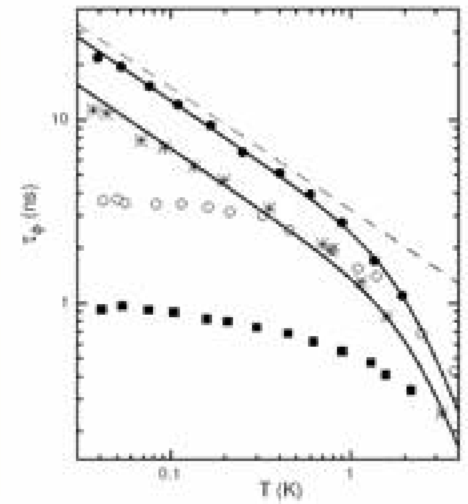


FIG. 3: Phase coherence time τ_ϕ versus temperature in wires made of copper Cu(6N)b (■), gold Au(6N) (∗), and silver Ag(6N)c (•) and Ag(5N)b (○). The phase coherence time increases continuously with decreasing temperature in wires fabricated using our purest (6N) silver and gold sources as illustrated respectively with samples Ag(6N)c and Au(6N). Continuous lines are fits of the measured phase coherence time including inelastic collisions with electrons and phonons (Eq. (4)). The dashed line is the prediction of electron-electron interactions only (Eq. (3)) for sample Ag(6N)c. In contrast, the phase coherence time increases much more slowly in samples made of copper (independently of the source material purity) and in samples made of silver using our source of lower (5N) nominal purity.

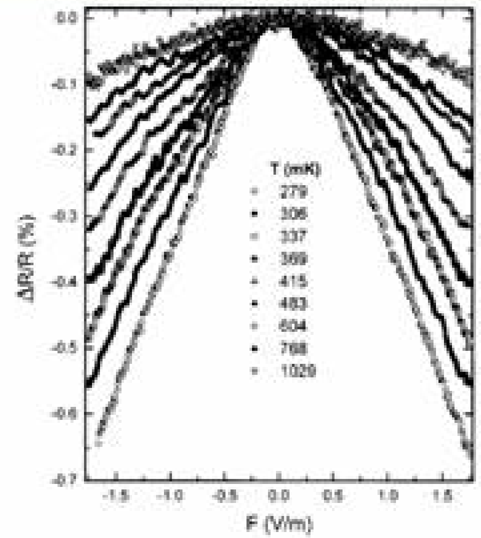


FIG. 12. Dependence of the differential resistance on F at several temperatures (sample No. 20).

Ovadyahu, 2001 ($T \approx .3K$):
Nonequilibrium effect.
i.e. out of linear transport!
Nonmagnetic (in InO_{3-x}).

$E \cdot 1mm \approx k_B T$!!!

We used *equilibrium* correlators to prove the vanishing of $1/\tau_\phi$ when $T \longrightarrow 0$.

Such correlators determine the linear response conductance (and magnetoconductance).

It becomes crucial that the exps probe the *linear response* ($I, V \longrightarrow 0$) regime.
Finite V opens more inelastic (hence, dephasing) channels!

Ovadyahu's results show that the conditions for that are more strict than usually expected!!!

PHYSICAL REVIEW B, VOLUME 63, 235403

Nonequilibrium dephasing in two-dimensional indium oxide films

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(Received 20 November 2000; published 14 May 2001)

We report on results of resistance R and magnetoresistance in diffusive indium oxide films measured down to $T=0.28$ K. Analyzing the data using weak-localization theory shows that the phase-coherent time τ_φ increases without bound as $T\to 0$. However, this result is obtained only when the voltage applied to the sample V is sufficiently small. When V is not small, τ_φ may appear to "saturate" while R continues to increase as $T\to 0$. Possible reasons for this intriguing behavior are discussed. It is argued that in out-of-equilibrium situations $R(T)$ and $\tau_\varphi(T)$ need not behave similarly. We suggest a heuristic picture, involving two-level systems, which might be consistent with our observations.

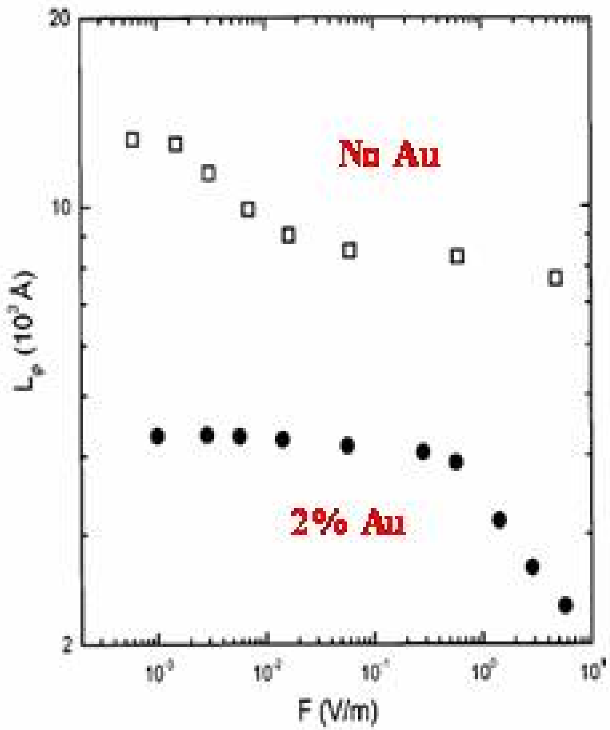


FIG. 9. The dependence of L_φ on F for In_2O_{3-x} (sample No. 1) and In_2O_{3-x}:Au (sample No. 4).

- For the "no Au" sample, an unusually minute driving field is necessary for Linear transport (note apparent constancy at higher fields!).
- But, electrons are <u>not heated</u> (confirmed from AA corections to R(T), as Mohanty et al did).
- Adding gold, facilitates getting linear!
- Systematic studies produced the very nontrivial condition for linearity of the transport, in terms of the electric field used for the measurement.

Experimental condition for linearity of the transport (NOT HEATING):

Can always be written in terms of a (surprisingly long) length:

$$eEL \ll k_B T$$

What is L?

Experimental result: $L = L_{er}$, (for $L_{er} \ll L_{sample}$)

The length to transfer the field-supplied energy away.

Based on a thorough study, unexpected theoretically.

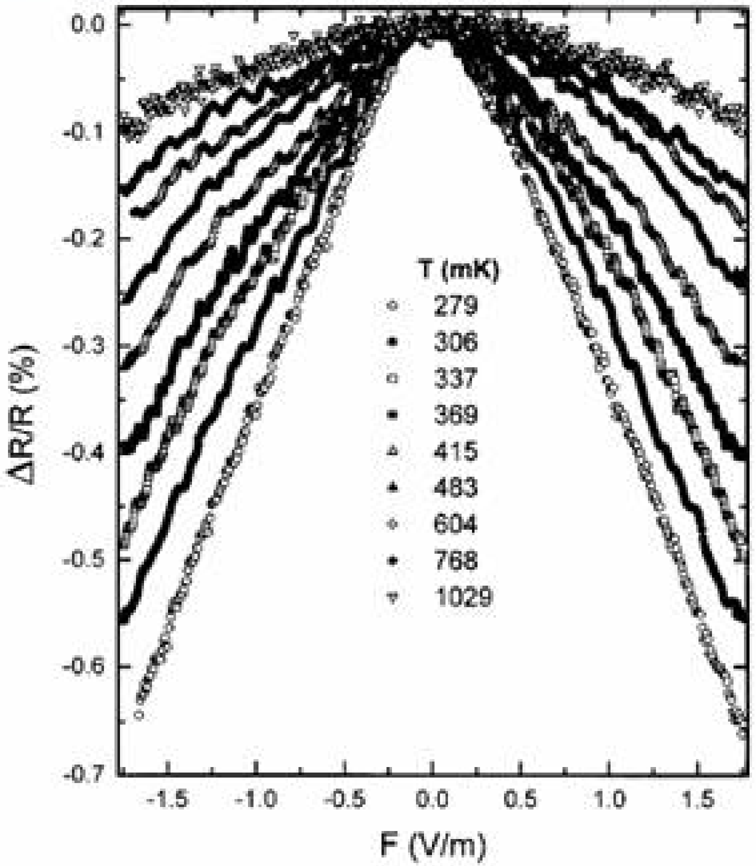


FIG. 12. Dependence of the differential resistance on F at several temperatures (sample No. 20).

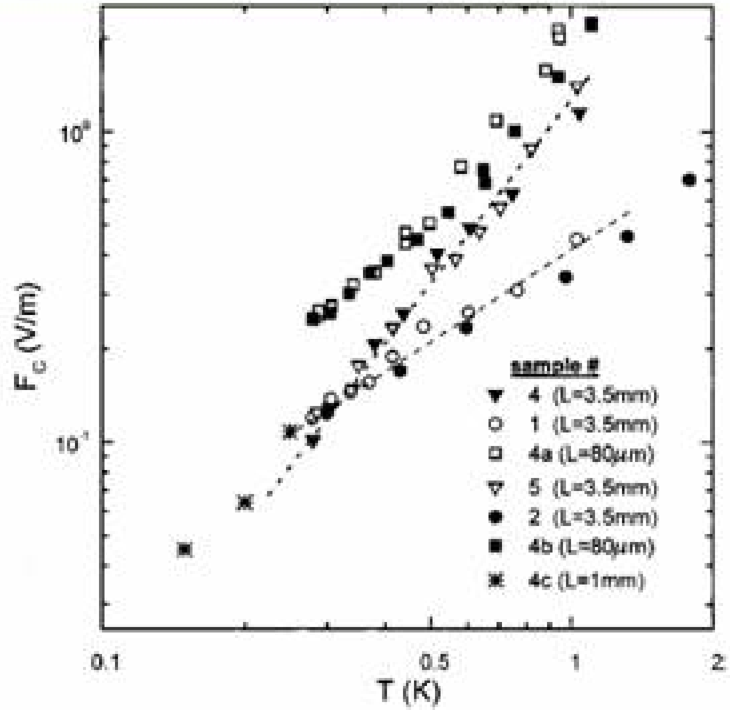


FIG. 14. The critical field (see text) for the various In_2O_{3-x} (circles) and In_2O_{3-x}:Au samples (other symbols) at various temperatures. Samples Nos. 4(a), 4(b), and 4(c) are from the same batch as sample No. 4 except that, for L is 80 μm, and for sample 4(c) $L = 1$ mm (the latter was measured by D. Shahar). Dashed and dotted lines depict slopes of 1 and 2, respectively, as guides to the eye.

The Real Question:

- How can the electric field cause dephasing without heating?

- Possible in principle! Precise answer here seems to depend on TLS's

Qualitative explanation

- e's and TLS are well coupled.
- TLS weakly coupled to bath, via $\tau_{i,TLS}$ (but better than e's!), their c_v >> that of the e's.
- e-TLS-bath channel gives dominant energy-relaxation.
- e's dump all field energy into TLS, whose temp changes little, rate of relaxation to bath: $\tau_{i,TLS}$.

⇓ **excitation (dephasing) with no heating!**

Another Intriguing Exp Result:

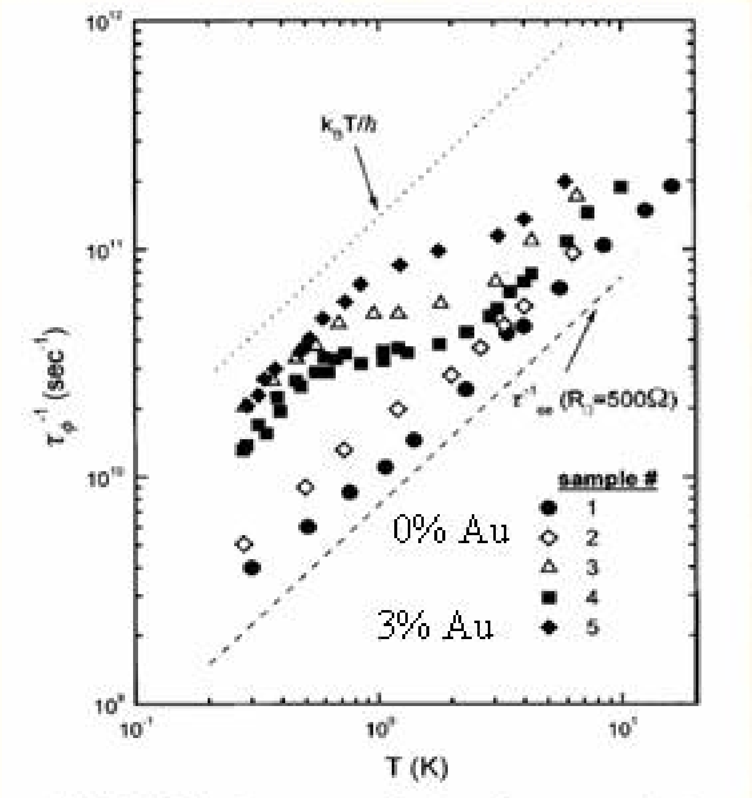
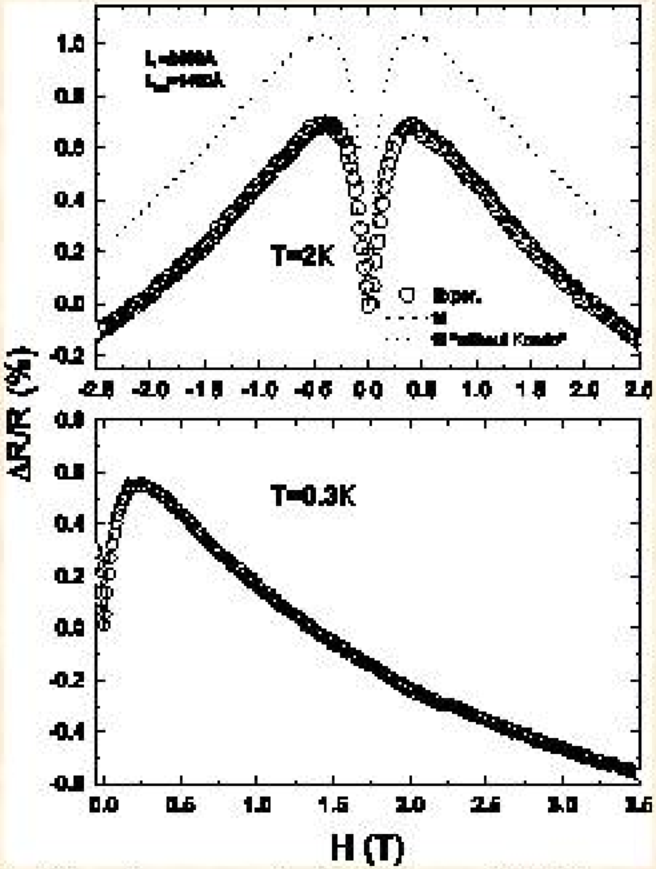


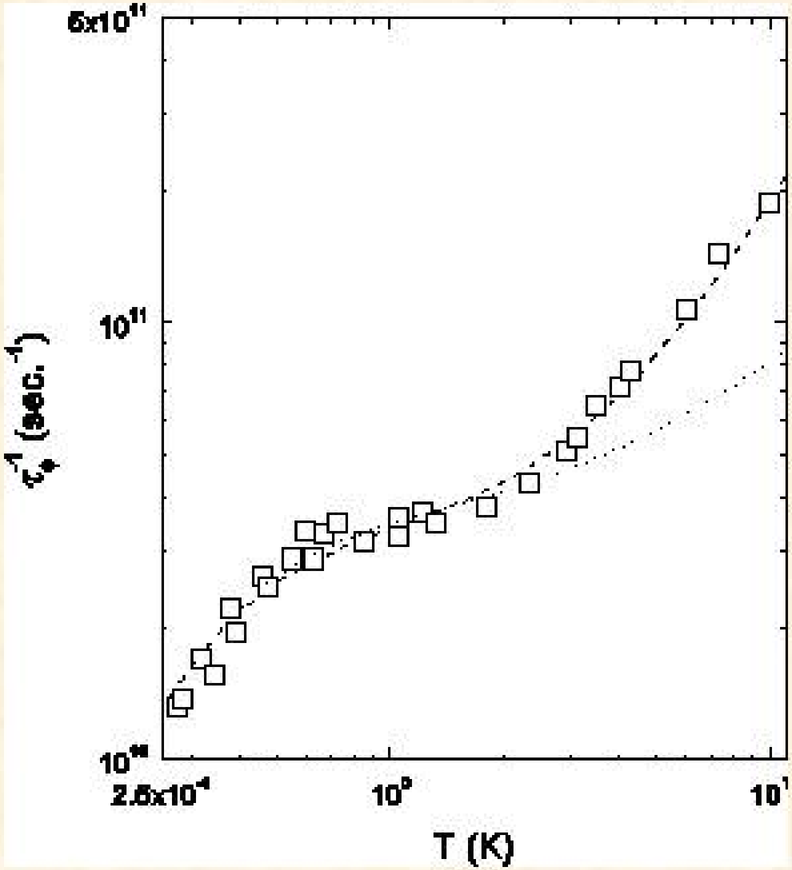
FIG. 11. Dephasing rates as a function of temperature for the studied films. These were obtained from the MR data at small F (typically 6×10^{-4} V/m at T=0.28 K, 3×10^{-3} V/m at 1 K, and 0.3 V/m at higher temperatures). For comparison, we include the electron-electron dephasing rate $\tau_{\varphi ee}^{-1}$ expected of a 2D system with $R_\square$ = 500 Ω (based on Ref. 20).

- **Doping the samples with more Au, leads to quasi-saturation of $1/\tau_\phi$, but followed by a rapid decrease at lower T! (as in the IFS model)**
- **Au goes into a O (or O_2) vacancy– a large rattling cage – may have a few minima structure.**

Exp. results, disordered InO:Au, Zvi Ovadyahu

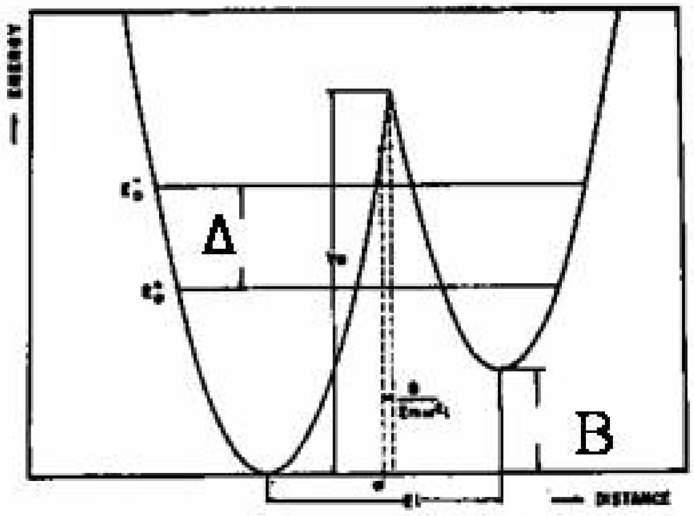


MR for InO_{3-x}:Au sample (thickness 200A with 2% Au). Dashed lines are fits to theory using a single $1/\tau_\phi$ for each of the temperatures Shown, one above and one below the anomaly.



$1/\tau_\phi$ vs T for the same sample. The dotted/dashed lines are fits to our theory with a symmetric well, using a reasonable prefactor and Δ=.3K, and adding the standard e-e AAK 2D/3D result.

A Double-minimum TLS model (IFS)



Ω_0 is the tunneling matrix-element between the two wells. A Born-appr calculation for n_s impurities of x-section σ_0 in a unit volume, for electrons with Fermi velocity v_F at temp T, gives ($4\alpha^2\beta^2$ is the well asymmetry parameter, $2\Omega_0/\Delta$ (=1 in the symmetric case):

$$2\Delta = 2\sqrt{\Omega_0^2 + B^2}.$$

$$\frac{1}{\tau_{in,s}} = \frac{4(\alpha\beta)^2 n_s v_F \sigma_0}{\cosh^2(\Delta/(k_B T))},$$

Averaging the result over the TLS distribution:

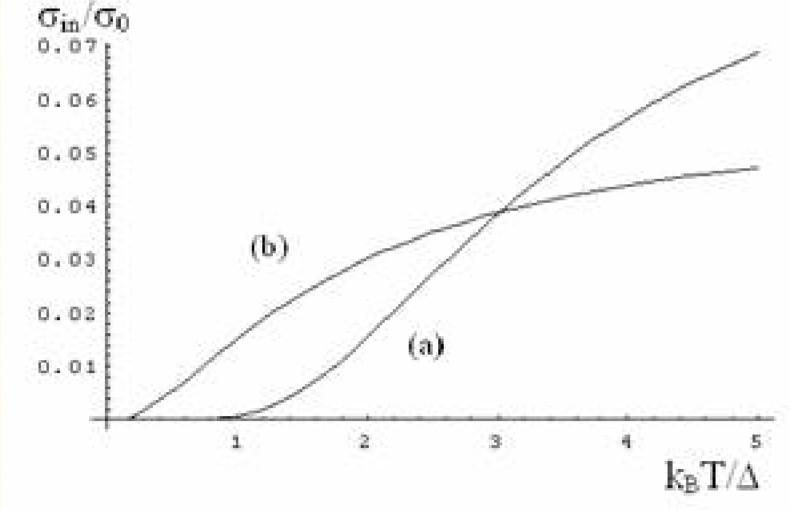


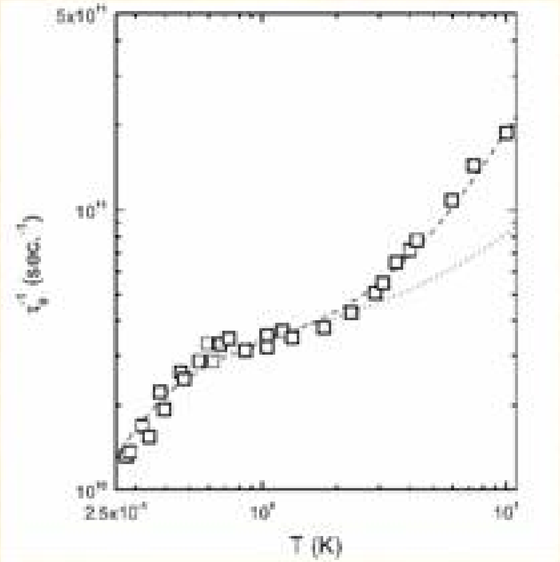
Figure 1.4. The inelastic cross-section of the TLS as a function of $k_B T$. (a) A single TLS (Eq. 1.12) with $B = 3$ and $\Omega_0 = 1$ (all energies in the same units). (b) The cross section averaged over the distribution of Eq. 1.14, with $B_{max} = 20$, $\Omega_{min} = 0.2$, and $\Omega_{max} = 2$. Note the qualitative similarity between these results and the hump of Fig. 3. Adding the electron-electron contribution as in Ref. [4] produces a reasonable fit of the experimental results with a TLS model,see Fig. 3.

We use a conventional TLS distribution, as in the theory of 1/f noise: B and $\ln\Omega_0$ are uniform between 0 and B_{max} and Ω_{min} and Ω_{max}. It was suggested by IFS to be relevant for the low-temp Dephasing problem.

Decoherence, CONCLUSIONS

- Mesoscopic Physics helps us understand fully the issue of decoherence (limiting the quantum behavior), which happens around τ_Φ, the (de)coherence time.
- Decoherence rate vanishes, as $T \longrightarrow 0$!!!
- Other cases where TLS are relevant (Josephson qbits!!!).

Interesting Physics for low T!



Questions for the future:

- **What are the physically relevant "soft" impurity potentials?**
- **Fuller understanding of nonequilibrium behavior.**
- **A larger body decoheres faster. How can we avoid that? Glauber states? LRO???**
- **Other cases where TLS are relevant (Josephson qbits!!!).**

The end

Thanks for attention!!!

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